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Potential of On-line Simulation for Fault Detection and Diagnosis in Large Commercial Buildings with Built-up HVAC Systems

Element 5 - Integrated Commissioning and Diagnostics
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Energy Systems Laboratory, Texas A&M University

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Potential of On-line Simulation for Fault Detection and Diagnosis in Large Commercial Buildings with Built-up HVAC Systems

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DISCLAIMER

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1. EXECUTIVE SUMMARY

Typical buildings consume 20% more energy than necessary due to inefficient operational procedures, non-optimal control schedules, and system faults. To realize this potential for energy performance improvement, the system faults must be detected, the mechanical and electrical problems diagnosed, and optimal control schedules and operating sequences developed and implemented. Today, these tasks must be conducted by well trained engineers using field measurement, specialized engineering analysis, and testing. Due to a lack of engineers skilled in operational optimization and the length of the process, performance optimization has been limited to a small fraction of the building stock. Consequently, excessive amounts of energy are wasted daily in existing buildings.

Simulation programs, such as DOE-2 and BLAST, are sometimes used for building system sizing and optimization during the design phase. More recently, other software programs, such as AirModel, have been developed to identify system faults, diagnose problems, and optimize system operation in existing buildings.

This report presents the results of a study of the potential for using simulation programs for on-line fault detection, problem diagnosis, and operational schedule optimization for large commercial buildings with built-up HVAC systems.

This study reviewed over a dozen simulation programs and determined that AirModel and EnergyPlus were most suitable for initial use in the on-line simulation applications that are the focus of this study. Relevant characteristics of these programs include the following:

(1) EnergyPlus is a detailed system performance simulation program. It can perform detailed load and system performance simulation.
(2) AirModel is a simplified system performance simulation program. It can perform simplified load and detailed system performance simulation. It differs from EnergyPlus in the level of detail of the building load modeling, including the number of zones. It allows the modeling of actual system performance, such as leaking dampers.
(3) Both EnergyPlus and AirModel have the capability to: (a) identify in-efficient operation at the whole building level, (b) identify major time invariant mechanical systems, (c) develop improved and optimized operational and control schedules and set points, and (d) project potential energy savings.
(4) Both EnergyPlus and Airmodel can be used for on-line simulation and fault detection after revising the input structures of the program.
(5) Airmodel can be embedded in existing energy management and control systems. On-line simulation can be conducted without major revision to the program.

Two case studies in which AirModel was used off-line to identify and diagnose system problems at the whole building level are presented. These cases studies illustrate to potential value of on-line simulation.

Two phase demonstration of on-line simulation is recommended. During the first phase, a commercial building will be selected. The building energy consumption and weather data will be measured in real time. AirModel will be run in parallel to the building operation. An interface will be developed to integrate the building automation system and AirModel input and output. Faults will be identified using discrepancies between the measured and simulated energy consumption. A manual of simulation based functional test procedures will be developed.

During the second phase, EnergyPlus will be used to identify building level faults as conducted in the first phase by AirModel. Currently, a number of system models are not developed for EnergyPlus. AirModel will be used to identify the system level faults, such as AHUs, chillers, and boilers. The potential and capabilities of the simulation based functional test will be documented based on the field application. A manual of fault diagnosis procedures will be developed for use with simulation programs.

2. BACKGROUND AND OVERVIEW OF POTENTIAL FOR DETECTING AND DIAGOSING FAULTS USING ON-LINE SIMULATION

There is an increasing realization that many buildings do not perform as intended by their designers. Reasons include faulty construction, malfunctioning equipment, incorrectly configured control systems and inappropriate operating procedures. Changes in the use or configuration of buildings without corresponding changes in systems or operating practices often contribute to these problems. Occasionally the problems are caused or compounded by design errors.

The first step in detecting and diagnosing such problems is the evaluation of building performance. A quantitative evaluation of performance requires a baseline or reference, against which to compare the actual performance. Possible sources of such a baseline include:

1. The previous performance of comparable buildings
2. The current performance of comparable buildings
3. The previous performance of the building in question
4. The intended performance of the building in question

In the first case, the performance of the building in question is compared to that of similar buildings using a database of the actual performance of a statistically selected sample of comparable buildings. The comparison is usually made in terms of whole building electricity and fuel consumption. This 'benchmarking' process can provide an approximate assessment of relative performance from very modest input data, typically building type, floor area and geographical location. Benchmarking is a useful screening tool, allowing attention to be focused on those buildings that appear to be performing poorly (add references).

In the second case, campuses or chains of comparable buildings with suitable monitoring capabilities may be compared on the time-scale of an hour to a week to detect the onset of operational changes or malfunctions that have a significant effect at the whole building level (reference?). This quasi-real-time form of benchmarking provides a relatively simple method of detecting significant degradations in performance before the cumulative effects of that degradation become severe.

In both the first and second cases, simple regression models are typically used to correct for differences between the conditions under which the actual performance is observed and the conditions for the baseline. However, simulation models are starting to be used as interpolation tools for more sophisticated benchmarking where more information about the buildings and their energy systems is available.

In the third case, the previous performance can be represented using a 'calibrated simulation', in which the parameters of the model are adjusted to minimize the difference between the predicted and measured performance over a selected period. The model can either be a detailed first principles model, such as EnergyPlus (Crawley et al. 2000), DOE-2 (LBNL 1982) or ESP (ESRU 2000), a simplified first principles model, such as AIRMODEL (Liu and Claridge 1998), or an empirical model, such as an artificial neural network (Kreider and Haberl 1994). In addition to providing a baseline for future performance, first principles models can also be used to identify more efficient operating strategies. Detailed first principles models tend to be over-parameterized for the measurements that are available in practice, suggesting that simplified first principles models may be more appropriate. This approach is discussed in a later section.

In the fourth case, use of a whole building simulation program is the natural method of representing intended performance. Comparison of actual and intended performance can be made either during commissioning or during routine operation. In the second, third and fourth cases, comparisons of energy use, peak demand and comfort conditions can be made on time-scales ranging from hours to weeks. In general, a longer time-scale results in greater accuracy of the prediction but less information that may be useful in diagnosing the nature of any faults or problems.

The second step is to identify the faults in a building by comparing the intended performance with the actual performance. This requires that the actual energy consumption (such as whole building electricity, heating, and cooling energy consumption) be measured along with weather and room conditions. These measurements are compared with the baseline performance and any differences analyzed to determine the faults.

The third step is to diagnose the problems if the measured performance differs from the expected or predicted performance. This can be accomplished by using one or more of the following approaches:

1. Inspect building and measure major building operational and control parameters, such as system operation schedules, supply water temperatures, supply air temperatures, etc. to identify faults
2. Conduct numerous short term measurements with dedicated meters. Input measured parameters to a specialized system model(s) or component model(s) to identify possible problems.
3. Calibrate baseline model(s) to match the simulation output to current measured energy performance data by adjusting input and operational parameters.

The first approach can identify major mechanical and electrical problems, such as broken VFDs, and damaged valves or dampers. If engineers conduct the field inspection, the control sequence may be checked as well. However, it is often hard to identify problems that only occur under different operating conditions. For example, it is hard to identify a leaking hot water valve if the inspection is conducted during winter when the valve is controlled open or it will be hard to detect chilled water hunting if the inspection is conducted during summer when the system is not hunting.

The second approach is useful for identifying problems with a particular component or set of components. This approach will be developed and integrated into Building Automation Systems (BAS) as the declining cost of sensors makes it practical.

The third approach requires that building energy consumption be measured. The building energy consumption can be measured using dedicated meters or meters installed as part of the BAS. The operational schedules, control parameters, envelope parameters, and or occupancy schedules are adjusted as physically appropriate in the input section of the baseline model. The baseline model results are then compared with measured consumption. If there are significant differences, building parameters and schedules are adjusted to match the simulation output with measured performance.

If the operational schedules in the original baseline model are changed to match the simulation with measured performance (energy consumption and room conditions), the deviation of the changed operation and control schedules from the original schedules is the cause of the poor performance. The fault or faults are diagnosed. This approach can be implemented from remote locations or on site. This approach can effectively locate the faulty devices and the nature of the problem(s). It can also identify historical problems and problems that occur under other weather and occupancy conditions, providing comprehensive system diagnosis capabilities.

The exact mechanical problems may not be identified explicitly. For example, this approach may identify a leaking control valve. But it may not determine whether the leakage is due to an excessive pressure difference or a stuck valve core. On-line simulation cannot entirely replace field inspection. A field visit should be performed to identify the problem and repair should be performed accordingly. Using simulation to assist in fault detection and diagnosis can maintain high building performance with minimum cost.

3. REVIEW OF SIMULATION PROGRAMS

A large number of simulation programs have been developed for building system design and/or design optimization. Some of them are more suitable for fault detection and diagnosis than others. This section reviews the simulation programs available with particular attention to features needed for fault detection and diagnosis.

DOE lists over 100 building energy simulation programs on its website (http://www.eren.doe.gov/buildings/tools_directory/database). Appendix A presents brief summary information for 16 selected programs as shown in Table 3-1.

Table 3-1. The 16 programs reviewed for use in on-line simulation of large buildings.

		Detailed general purpose detailed whole building energy simulation programs
1	APACHE	thermal design, thermal analysis, energy simulation, dynamic simulation, system simulation
2	BLAST	energy performance, design, retrofit, research, residential and commercial buildings
3	DOE-2	energy performance, design, retrofit, research, residential and commercial buildings
4	EnergyPlus	energy simulation, load calculation, building performance, simulation, energy performance, heat balance, mass balance
5	HAP v4.0	energy performance, load calculation, energy simulation, HVAC equipment sizing
6	TRACE 700	energy performance, load calculation, HVAC equipment sizing, energy simulation, commercial buildings
7	VisualDOE	energy performance, design, retrofit, research, residential and commercial buildings
		Simplified general purpose whole building energy simulation programs
1	AirModel	Building commissioning, fault detection, and savings evaluation
2	ASEAM	energy performance, existing buildings, commercial buildings
3	System Analyzer	energy analyses, load calculation, comparison of system and equipment alternatives
		Specialized building energy simulation programs
1	HBLC	heating and cooling loads, heat balance, energy performance, design, retrofit, residential and commercial buildings
2	HVACSIM+	HVAC equipment, systems, controls, EMCS, complex systems
3	SPARK	object-oriented, research, complex systems, energy performance
4	TRNSYS	design, retrofit, research, energy performance, complex systems, commercial buildings
		Data visualization/analysis programs
1	ENFORMA	data acquisition, energy performance, building diagnostics, HVAC systems, lighting systems
2	Visualize-IT Energy Information and Analysis Tool	energy analysis, rate comparison, load profiles, interval data

The simulation programs reviewed that are suitable for use on large commercial buildings are categorized in the table into the following groups:

1. Detailed general purpose building energy system simulation programs, which simulate both building envelope and HVAC systems.
2. Simplified general purpose building energy system simulation programs, which simulate both building envelope and HVAC systems.
3. Specialized building energy simulation programs which may be intended primarily for research purposes, or may simulate only part of the building, such as the loads.
4. Data visualization programs that are intended primarily for viewing or analyzing measured energy consumption data.

A simulation program capable of simulating the complete building system is required to detect and diagnose HVAC system faults since both building thermal loads and systems must be simulated during the process. Hence, only the programs in shown in the first two categories are suitable for the on-line fault detection application to be investigated. The best candidate within the detailed model-based simulation programs is EnergyPlus, since it has the following features:

1. Users can set the simulation time-step and the simulation period. For example, a particular fault detection process may only require several hours of simulation instead of a whole year. The time-step can vary from one minute to one hour. This is useful for detecting dynamic problems.
2. Users can construct any system using basic blocks. Most other programs can only simulate pre-defined systems, which are often incapable of representing the actual systems in buildings.
3. Users can select individual output parameters. This is helpful in analyzing the results.
4. EnergyPlus has (or will have) all the features of DOE-2 and BLAST and includes some features of TRNSYS and similar programs.

EnergyPlus is also a public domain program, which means that documentation of algorithms used is available.

The main candidates among the simplified simulation programs are ASEAM and AirModel. AirModel is specifically designed for fault detection and building commissioning; the following features make it the best choice for on-line application:

1. Actual system performance can be simulated. For example, air leakage in terminal boxes can be simulated.
2. A good graphic interface for the output makes comparison of measured and simulated results easy.
3. Input requirements are very simple.

Review of EnergyPlus

EnergyPlus is a new program, although based on the most popular features and capabilities of BLAST and DOE-2. EnergyPlus largely comprises new, modular, structured code written in Fortran 90. It is primarily a simulation engine - it is intended that user interfaces will be developed by the private sector. Input and output are simple, comma-separated, ASCII text files and the input language are much simpler than those of DOE-2 or BLAST.

EnergyPlus contains detailed system and load simulation models. Most common systems can be simulated using EnergyPlus. Its accuracy is expected to be similar to, or better than, DOE-2 or BLAST.

The modular structure is the most significant advantage of EnergyPlus over DOE-2 or BLAST. This feature makes it the best simulation program for building fault detection and diagnosis applications for the following reasons:

- Engineers can add or modify modules to reflect actual system performance, such as terminal box leakage rate. Consequently, it has the potential to predict actual system behavior instead of only the “ideal behavior” simulated by most programs, so real faults can be identified. An idealized simulation can identify a deviation from ideal behavior, but cannot simulate the non-ideal behavior of many typical faults.

- Engineers can use the energy meter feature to categorize the energy consumption by type, resources, and systems. Energy inefficiency can be identified by comparing the utility bills or BAS measured energy consumption data with simulated energy consumption data.
- EnergyPlus allows the specification of any simulated parameters as outputs, such as chilled water return temperature and chilled water flow rate. Engineers can specify BAS measured parameters as output parameters in the EnergyPlus program. The simulated data can be compared with BAS measured data. Most system faults can be identified easily if modeling and measurement errors can be quantified.
- EnergyPlus makes it easy to simulate part of a building. For example, air handling units can be simulated using a dummy central plant. This feature (1) minimizes the simulation effort, (2) decreases cost, and (3) allows detailed trouble shooting in local areas or systems.
- EnergyPlus allows the user to specify the simulation time-step. Engineers can use this feature to identify peak demand control problems and develop improved demand control strategies. This feature will also allow engineers to identify dynamic mechanical and control problems, such as damper hunting, since EnergyPlus will model load changes but not control system instability.
- EnergyPlus allows flexible weather data input. Users can create their own weather data files using specified formats. This allows fair comparison of measured consumption and simulated consumption.
- EnergyPlus is a simulation engine and input files will be hard to create and manage until graphic interfaces are developed. An interface intended for building operation applications should have special features for fault detection and diagnosis purposes since the input and output requirement are very different from the requirements for building design and design optimization.

Review of AirModel

AirModel is a software package developed for use in the building continuous commissioning and optimization process at the Energy Systems Laboratory, Texas A&M University (Liu 1997). Currently, the Energy Systems Laboratory at the University of Nebraska maintains and updates the program. It simulates building heating, cooling, and electricity consumption when provided with suitable building information and weather (dry bulb temperature and wet bulb temperature or relative humidity) data. It identifies system faults by comparing the simulation results with measured results, and optimizes the system operation schedule automatically. It accepts data of any time interval, such as hourly, daily, or monthly, and can also be used with bin weather data. A program called Voyager, developed at Washington University (Lantern 1990), is used as the primary graphic interface to explore simulation results.

AirModel was developed by drawing on the extensive engineering experience of the Continuous Commissioning group at the Energy Systems Laboratory at Texas A&M University. The first version was completed in 1993 and Version 6 was completed in 2000 at the Energy Systems Laboratory, University of Nebraska. AirModel has been used by its developers since 1993 to identify operation and maintenance problems.

AirModel is a system-based simulation program. The part of the building served by a single AHU is simplified into one or two zones. It treats all the major AHU configurations: (1) dual duct systems, (2) single duct with terminal reheat, and (3) single zone systems. It can simulate both variable air volume and constant air volume systems. The pre-heat coil can be placed in either the mixed air stream or outside air stream. The outside air can be directly introduced into an AHU or be pre-treated using a dedicated unit. The heating coil can be placed either before or after the cooling coil for single zone units. Multiple AHUs can be simulated using AirModel.

AirModel requires the following input: outside air conditions and measured energy consumption, and building and system information. Table 3-2 lists the weather and energy input parameters required.

Table 3-2: Description of Weather and Energy Input File

Column	Definition	Note
1	Site number	Any integer number
2	Month	Integer number from 1 to 12
3	Day of the month	Any integer number from 1 to 31
4	Year	Integer number
5	Decimal year	Any real number
6	Julian Year	Real number
7	Hour	Any number from 0 to 23 or from 0 to 2300
8	Dry bulb temperature (°F)	Real number
9	Dew point temperature (°F) or Relative humidity (0 to 1)	Real number
10	Measured chilled water consumption (MMBtu/hr)	Real number
11	Measured hot water consumption (MMBtu/hr)	Real number

The building is characterized using 36 envelope and system inputs or schedules for each AHU and 19 inputs or sets of component characteristics for the plant.

AirModel conducts a detailed energy and indoor comfort simulation. It reports 43 categories of variables (See Table 3-3 for the output variable list), including airflow to each zone and through each duct, CO2 level in each zone, and energy consumption.

The graphical interface and simplified input information allow quick calibration of the simulation model. This is one of the major advantages of AirModel over DOE-2 or similar programs. The graphic interface can present each parameter in both time series and scatter plots. Any two parameters can also be compared in time series and scatter plots. Figure 1 is a typical screen used in the model calibration process. The simulated and measured chilled water energy consumption are compared using both time series and scatter plots.

AirModel uses a simplified model to estimate building thermal loads. The effect of thermal mass is estimated using representative room weighting factors. It has good simulation accuracy for daily and hourly simulation since envelope thermal loads typically have a very limited impact on the building thermal energy consumption in large office buildings

Table 3-3: Summary of AirModel outputs

Column	Definition
1	Month
2	Day
3	Year
4	Hour
5	Day of Week
6	Ambient Temperature ^oF
7	Ambient dew point (^oF)/relative humidity (%)
8	Measured chilled water consumption (MMBtu/hr)
9	Measured hot water consumption (MMBtu/hr)
10	Measured whole building electricity consumption (kWh/h)
11	Simulated chilled water consumption (MMBtu/hr)
12	Simulated hot water consumption (MMBtu/hr)
13	Simulated whole building electricity consumption (kWh/h)
14	HVAC operation cost (Heating + Cooling + Fan Power) ($/hr)
15	Residue of simulated chilled water consumption (MMBtu/hr)
16	Residue of simulated hot water consumption (MMBtu/hr)
17	Residue of simulated whole building electricity consumption (kWh/h)
18	Supply fan power consumption (kWh/h)
19	Interior zone relative humidity (%)
20	Exterior zone relative humidity (%)
21	Interior zone CO_2 level (ppm)
22	Exterior zone CO_2 level (ppm)
23	Outside air intake fraction (%)
24	Cold air flow to interior zone (cfm)
25	Hot air flow to interior zone (cfm). Zero flow for SD systems
26	Cold air flow to exterior zone (cfm)
27	Hot air flow to exterior zone (cfm). Zero flow for SD systems
28	Cold deck temperature (^oF)
29	Hot deck temperature (^oF)
30	Mixed air temperature (^oF)
31	Pre-cooling coil temperature (^oF)
32	Pre-heating coil temperature (^oF)
33	Pre-cooling energy consumption (MMBtu/hr)
34	Cooling energy consumption of main cooling coil (MMBtu/hr)
35	Pre-heating energy consumption (MMBty/hr)
36	Heating (DD systems)/re-heating (SD systems) consumption (MMBtu/hr)
37	Chilled water supply temperature (^oF)
38	Main coil chilled water return temperature (^oF)
39	Pre-cooling coil chilled water return temperature (^oF)
40	Average chilled water return temperature (^oF)
41	Chilled water flow rate to the main coil (GPM)
42	Chilled water flow rate to the pre-cooling coil (GPM)
43	Total chilled water flow (GPM)

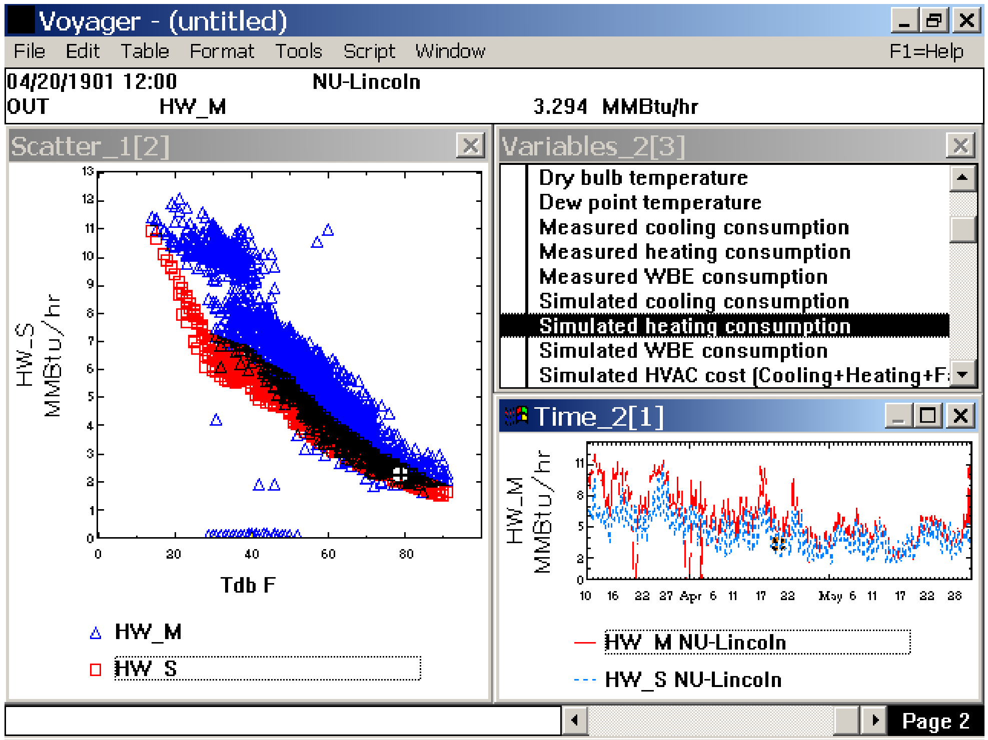


Figure 3-1: A Typical Screen during Model Calibration Process

4. DEMONSTRATION CASE STUDY I - DUAL DUCT AIR HANDLING UNITS

Building and HVAC System Information

The John Sealy South building is a 12-story in-patient hospital facility in Galveston, Texas with a total conditioned floor area of 298,500 ft^2. The building has light-colored brick walls with recessed windows to limit sunlight exposure. The windows make up only 7% of the wall area. The exterior zone of the building is occupied by patient rooms, while the interior zone contains nurses' stations and other types of office spaces.

Lighting and people are the major sources of internal gain for this building. Average lighting electricity consumption is 2.75 W/ft^2 and corridors are substantially over-lit. At night, most of the lighting in patients' rooms is turned off, while interior zone lights remain on.

There are four dual-duct constant air volume systems (Figure 4-1). The total design airflow is 302,000 CFM with 30% outdoor air intake. The building receives chilled water and steam from a central plant.

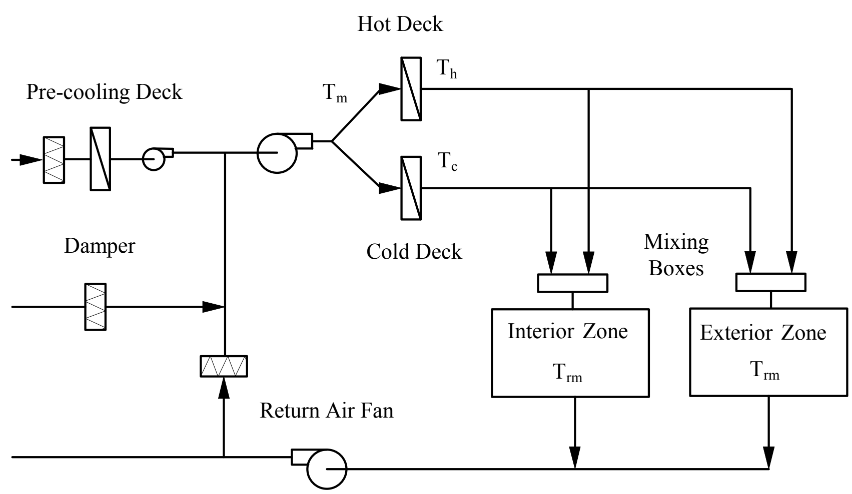


Figure 4-1: Schematic Diagram of Typical AHU System for John Sealy South Building

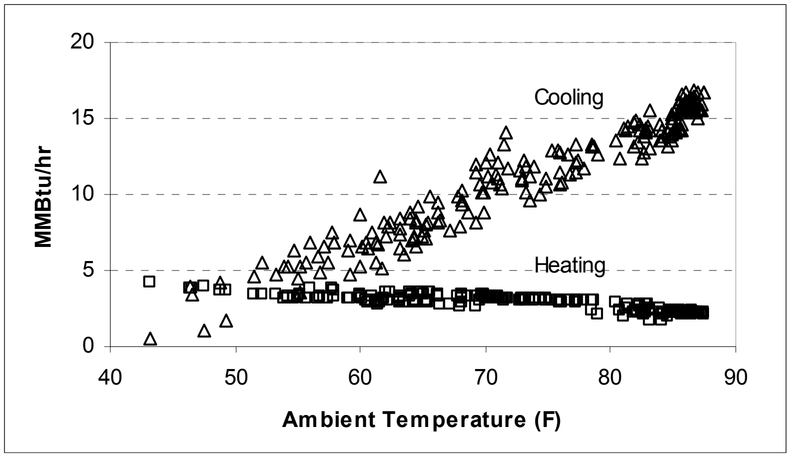


Figure 4-2: Measured Daily Average Chilled Water and Heating Water Energy Consumption Versus Ambient Temperature

Baseline Development

The baseline simulation model that represents the expected performance was developed using the envelope design information and the then current BAS control system set-points and schedules. Table 4-1 summarizes this information. The reference values of these parameters were collected during a site visit. No hourly weather data are available for Galveston, so measured weather data from an airport about 30 miles to the northwest were used for the case study. These data represent Galveston weather fairly well except during very hot summer days when the dew point temperature is 2°F to 3°F higher in Galveston. Most input parameters are determined from design drawings, air balance reports and reset schedules used by the BAS. Internal heat gain is estimated based on the measured electricity consumption of the lights and receptacles in the building and occupancy information. Solar gains are estimated using simple procedures suggested by Knebel [1983]; alternatively, those of Vadon et. al. [1993] may also be used. The effective values of the combined internal and the solar gains are then adjusted during model calibration, if necessary. When the gain values used are too low, the model will over-predict winter heating consumption and under-predict summer cooling consumption; the gains are then adjusted to more suitable levels. Infiltration is also difficult to determine by simple site observations. When the infiltration estimate is too low, predicted indoor humidity levels will be lower than measured values during humid weather. For other weather conditions, the infiltration may be assessed using the CO_2 level.

Table 4-1: Summary of Input Parameters

Symbol	Definition	Reference Values
T_o	Ambient dry bulb temperature	Houston Hobby Airport
T_{dp}	Ambient dew point temperature	Houston Hobby Airport
T_{rm}	Room temperature	72 °F
T_r	Return air temperature	77 °F
A	Total conditioned floor area	298,500 ft^2
f_{int}	Fraction of interior floor area to the total floor area	0.35
UA_{wall}	Total wall heat transfer coefficient	36,500 Btu/hr °F
UA_{win}	Total window heat transfer coefficient	16,000 Btu/hr °F
Q_{sol}	Solar heat gain	15,750 Btu/hr °F
$CFM_{inf,int}$	Air infiltration rate to the interior zone	0.2 ACH

$CFM_{inf,ext}$	Air infiltration rate to the exterior zone	0.4 ACH
q_i	Internal gain due to lighting and other equipment per unit floor area	2.42 W/ft^2
A_{pe}	Units of floor area for each person	120 ft^2
CFM	Total supply air flow rate	302,300 CFM
f_o	Outside air fraction	0.30
p_{fan}	Power consumption of the supply fan	625 hp
T_{pre}	Pre-cold deck set point	60 °F
T_c	Cold deck set point	55 °F
T_h	Hot deck set point	If T_o<80 °F then Min(90, 85-0.25(T_o-75) else 80 °F

The heating and cooling energy consumption from February 1993 through August 1993 was predicted using the reference values of input parameters. Figure 4-3 compares the measured and simulated heating and cooling energy consumption.

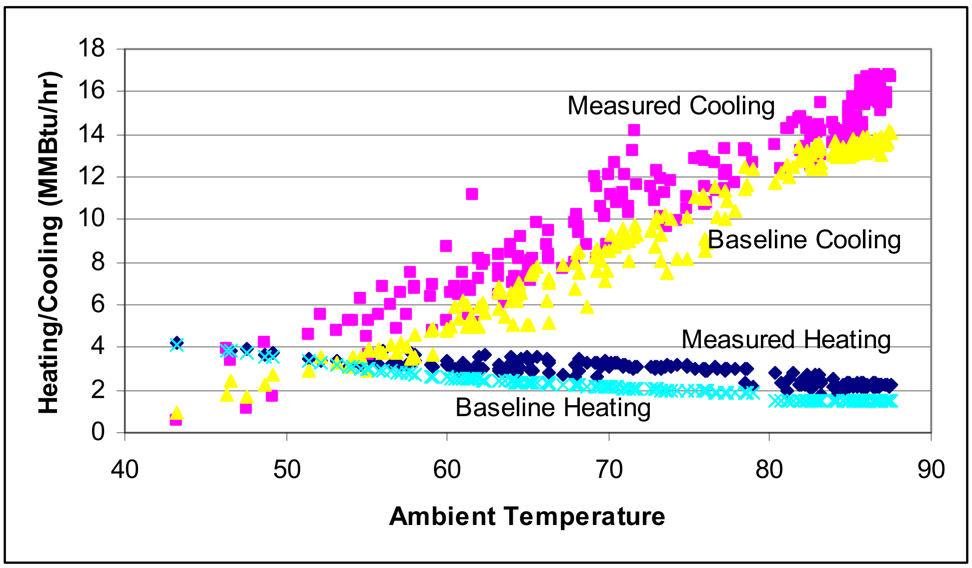


Figure 4-3: Simulated Baseline and Measured Heating and Cooling Energy Consumption

Fault Detection and Diagnosis

From Figure 4-3, the simulated baseline energy consumption values are 26% and 16% lower than the measured values for heating and cooling respectively. The HVAC systems are not functioning as designed.

Since both the simulated heating and cooling energy consumption are lower than the measured values, mass and energy balance indicated that the difference must have been due to: (1) the assumed total air flow rate being lower than the actual flow rate; or (2) the assumed cold deck temperature being higher than the real value or the hot deck temperature being higher than the assumed value, or both.

When the assumed total air flow is lower than the actual flow, the model will under-estimate both heating and cooling energy consumption by about the same amount. However, the difference between the simulated and measured cooling energy consumption is larger than the difference between the simulated and measured heating energy consumption. Therefore, the differences between the simulated and the measured values are not entirely due to the airflow rate.

When the assumed cold deck temperature is lower than the real value, the cooling energy difference is larger than the heating energy difference since the cooling coil must meet additional latent load, which does not require a corresponding increase in load on the heating coil. Based on this observation, it is concluded that the actual cold deck discharge air temperature is lower than the set-point due to malfunctioning control components or temperature sensors.

Consequently, the simulated pre-cooling deck discharge air temperature and cold deck discharge air temperature are adjusted to match the simulated and measured cooling and heating energy consumption values. It is found that the simulated cooling and heating consumption matches measured values within 5% when both the pre-cooling deck and main cold deck discharge air temperatures are assumed to be 52°F, and the hot deck air temperature is assumed to be 5°F higher than the set-point. Table 4-2 summarizes the intended or design values and the adjusted deck set-points.

Table 4-2: Summary of the Model Calibration Parameter Adjustment

Item	Schedule (EMCS)	Schedule (Adjusted)
Pre-cold deck temp. °F	60.0°F	52.0°F
Main-cold deck temp. °F	55.0°F	52.0°F

Hot deck temp. °F	If T_o<80 then
	Min(90, 85-0.25*(T_o-75))
	Else
	80
		If T_o<80 then
		Min(95, 90-0.25*(T_o-75))
		Else
		85

Figure 4-4 compares the measured and simulated heating and cooling energy consumption under adjusted control set points.

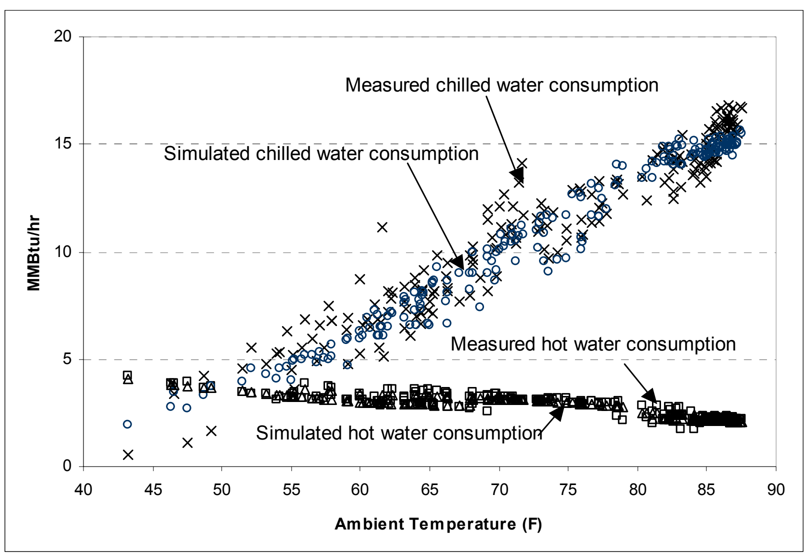


Figure 4-4: Comparison of Simulated and Measured Average Daily Heating and Cooling Energy Consumption Versus the Daily Ambient Temperature

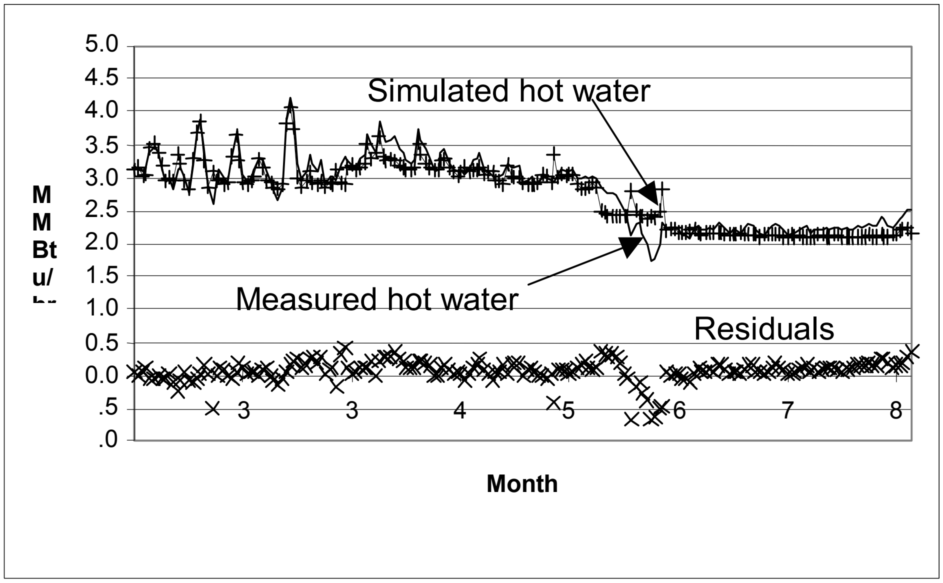


Figure 4-5: Comparison of Measured Heating Energy Consumption and Simulated

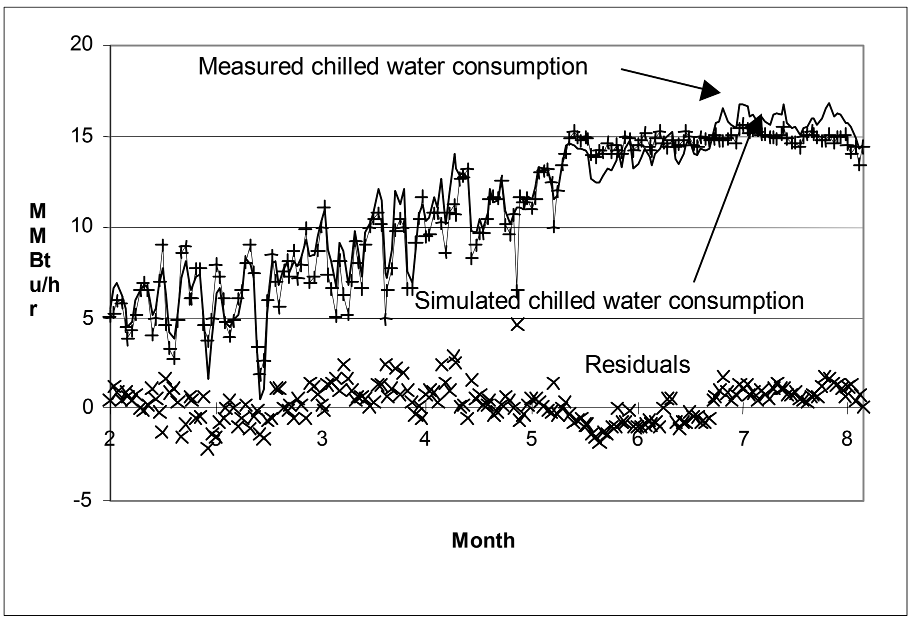


Figure 4-6: Comparison of Measured Cooling Energy Consumption and Simulated Cooling Energy Consumption with Adjusted Control Set-points

Field Verification

The hot and cold deck discharge air temperatures of all four AHUs were simultaneously measured using portable thermometers and the BAS. Table 4-3 summarizes the results.

Table 4-3: Comparison of Site Measured Deck Discharge Air Temperatures With Those Measured by BAS and Set Points

	Pre-cooling deck	Cold deck	Hot deck
Model Identified	52.0°F	52.0°F	85.0°F
Site Measured	52.8°F	51.5°F	85.0°F
BAS Measured	56.0°F	53.9°F	85.9°F
BAS Set Point	60.0°F	55.0°F	80.0°F

It was found that the model identified cold and hot deck temperatures that agree with the actual values within 0.5°F and hence had detected significant errors in the BAS measurements.
The low pre-cooling deck temperature was due to the control valve not being able to control the water flow under excessive pressure. The low cold deck and high hot deck temperatures were due to inappropriate temperature sensors, which are located directly down stream of the coils. The sensors were only 10 inches long and penetrated through a wall into the ductwork so they did not measure the average air temperature. Normally, an averaging sensor that samples the entire cross-sectional area is required to measure the coil leaving air temperature accurately.

Operational Optimization

The goal of optimizing the operating and control schedules is to minimize energy consumption while maintaining indoor comfort without expensive changes in the systems. In order to maintain indoor comfort in this building, the following conditions are required: 1) the hot deck supply air temperature should not be lower than 75 °F (23.8C) during hot summer days; and 2) the room relative humidity should be within the range of 30% to 60%.

AirModel can identify the optimal deck reset schedule automatically. It predicts the base energy consumption first under a given weather condition. Then, the operating conditions, such as cold deck and hot deck settings, are adjusted to reduce the cooling and heating energy consumption. If these parameter adjustments result in reduced energy consumption, while maintaining suitable room comfort and mechanical operation, the adjustment of parameters is continued following the same trend with reasonable step-size. This process is continued until the operating settings, which produce the minimum energy consumption, are identified.

Table 4-4 lists the operating schedules as specified by the designer, as operated in the base-case, and as optimized. The optimized operating schedules applied outside air reset in a way that decouples dehumidification and sensible cooling. The pre-cooling deck temperature is set as low as 52°F (11.1°C) so that it dries the outside air sufficiently so that the main cold deck discharge air temperature can be set based on the sensible cooling load.

Table 4-4: Comparison of Operating Schedules

Item	Design	Base-case	Optimized
O. A. treatment coil	If T_o>60 °F then 60 °F, else Off	If T_o>60 °F then 52.8 °F, else off	if T_o>60 °F then Min(54, 54-0.05*(T_o-60)) else off
Main cold deck	55 °F	51.5 °F	Min(59, 59-0.05*(T_o-50))
Hot deck	If T_o<80 then Min(90, 85-0.25*(T_o-75)) Else 85	If T_o<80 then Min(95, 90-0.25*(T_o-75)) Else 85	If T_o<80 then Min(85, 85-0.25*(T_o-60)) Else 75

Figure 4-7 compares the simulated cooling and heating energy consumption under the base-case and optimized operating schedules. The ambient air dry-bulb temperature is plotted on the horizontal axis. The cooling and heating energy consumption (in MMBtu/hr) are plotted on the vertical axis. The figure shows that the optimized schedule should reduce cooling consumption by approximately 1.0 MMBtu/hr to 2.25 MMBtu/hr with an average reduction of 1.95 MMBtu/hr and heating consumption by 0.8 MMBtu/hr to 1.25 MMBtu/hr with an average reduction of 1.13 MMBtu/hr. The simultaneous reduction of cooling and heating requirements indicates that the majority of the savings (2.26 MMBtu/hr) come from reduced reheat. The relatively higher cooling savings (0.82 MMBtu/hr greater than heating savings) indicate that the optimized schedule will remove less moisture, and increase the room relative humidity above base-case levels. It may be noted that there are sudden decreases of both the cooling and heating consumption when the ambient temperature is near 80 °F; this is due to the form of the hot deck schedule. The annual cooling savings are 17,100 MMBtu/yr, and annual heating energy savings are 9,911 MMBtu/yr. These energy savings reduce the annual energy cost by $141,100 for chilled water and $50,100 for steam. The total potential savings of $191,200/yr is 23% of the heating and cooling energy cost.

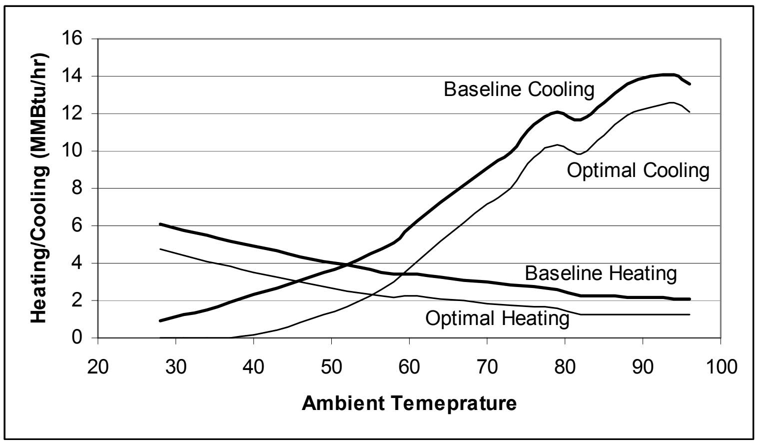


Figure 4-7: Comparison of Baseline and Optimal Heating and Cooling Energy Consumption

Figure 4-8 compares the simulated room relative humidity levels under the optimized schedule and under the base-case schedule. The predicted room relative humidity under the baes-case schedule was consistent with the BAS measured value. The optimized schedule is simulated to increase the room relative humidity to a maximum value of 57%, which is about 8% higher than the maximum value with the base-case schedule and 3% below the maximum acceptable value at this building.

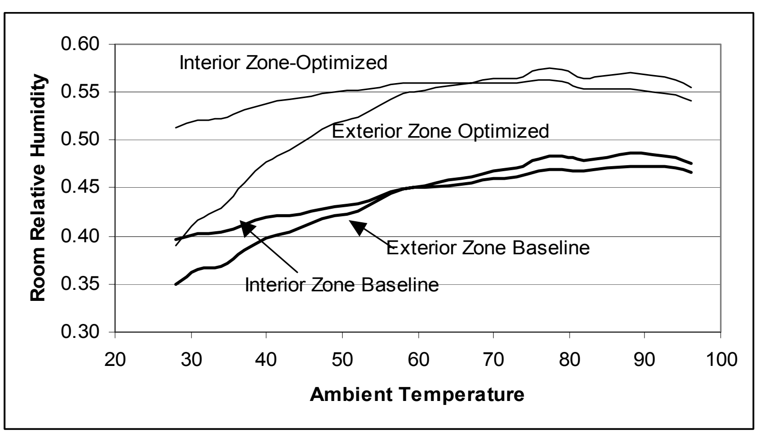


Figure 4-8: Simulated Room Relative Humidity Under Both Base-case and Optimal Operation and Control Schedules

Figure 4 -9 compares the simulated airflow rates through cold and hot air ducts under both the base-case and the optimized schedules. The base-case schedule has a cold air flow range of 130,000 CFM to 220,000 CFM and a hot air flow range of 75,000 CFM to 170,000 CFM, while the optimized schedule has a cold air flow range of 110,000 CFM to 250,000 CFM and a hot air flow rate range of 60,000 CFM to 190,000 CFM. The optimized schedule requires a larger flow range in each duct than the base-case schedule. However, this increase can be accommodated by the existing system, which has a capacity of 270,000 CFM for cold air and 220,000 CFM for hot air.

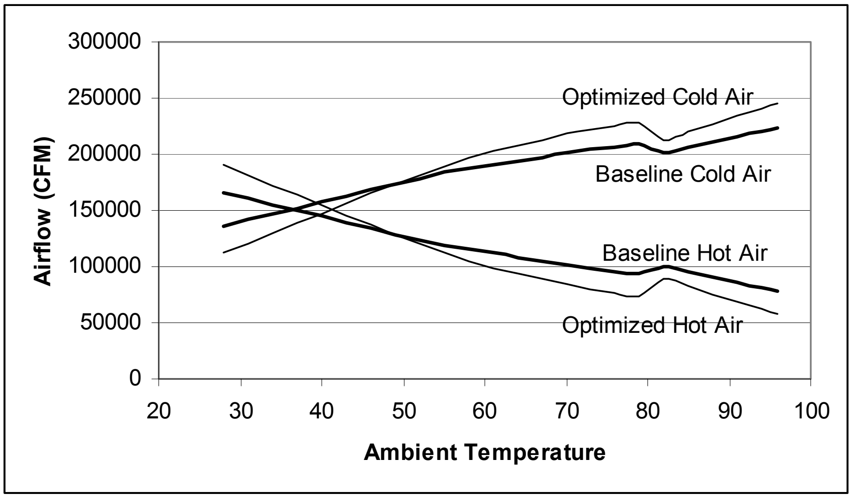


Figure 4-9: Comparison of Simulated Hot and Cold Airflow Rates Under Both Base-case and Optimal Operation Schedules

Implementation

The optimized cold and hot deck reset schedules were implemented using the BAS. The measured heating energy consumption is presented in Figure 4-10 for both the base-case and optimized periods. The measured cooling energy consumption is presented in Figure 4-11.

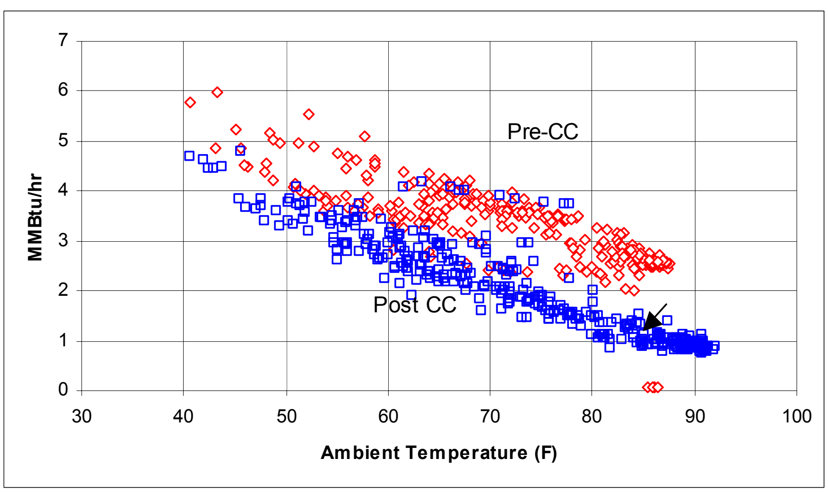


Figure 4-10: Comparison of Measured Heating Energy Consumption Under Both Base-case and Optimal Control Schedules

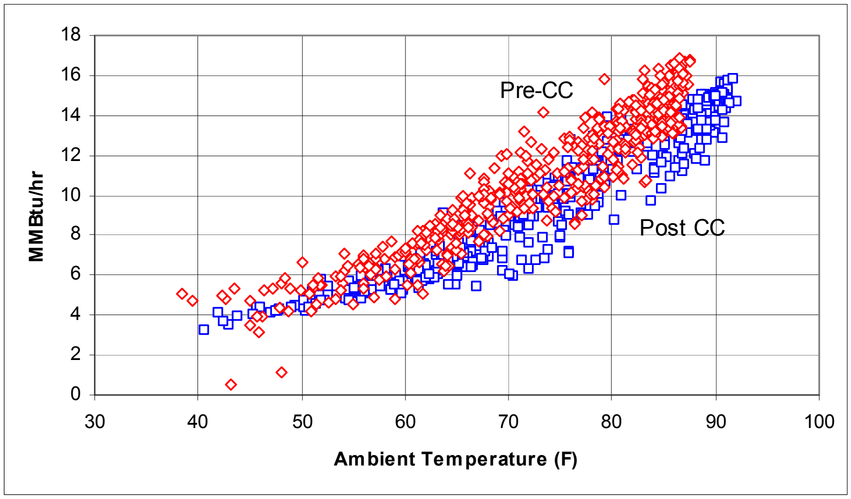


Figure 4-11: Comparison of Measured Cooling Energy Consumption Under Both Base-case and Optimal Control Schedules

The measured results show that the chilled water consumption is reduced by 1.5 MMBtu/hr to 2.5 MMBtu/hr as the ambient temperature varies from 30°F to 95°F. The heating energy consumption is reduced by 1.0 MMBtu/hr to 1.5 MMBtu/hr over the same temperature range. The results are consistent with the potential savings predicted by the calibrated models.

5. DEMONSTRATION PROJECT - SINGLE DUCT AIR HANDLING UNITS

Building and HVAC Systems

The Basic Research Building (BRB) at M. D. Anderson (MDA) Cancer Center is a seven-story building with 123,000 ft^2 gross floor area, which includes 93,000 ft^2 for the laboratory and office section, 20,000 ft^2 for a library, and 10,000 ft^2 for mechanical rooms and other purposes. The HVAC systems operate 24 hours per day.

Four single duct constant volume air handling units (AHUs) provide cooling and heating to the laboratory and office section. The design airflow rate is 150,000 cfm with 100% outside air. Figure 5-1 presents the schematic diagram of a typical AHU. The pre-heat deck set point is 55°F. If the outside air temperature is below 55°F, the pre-heat coil warms the air temperature to 55°F. If the outside air temperature is higher than 55°F, the pre-heat valve is closed. The cold deck temperature is set at 55°F. The room temperature is controlled using reheat. If the room temperature is below the set point, which varies from 72°F to 75°F from room to room, the reheat coil is turned on to maintain the room temperature.

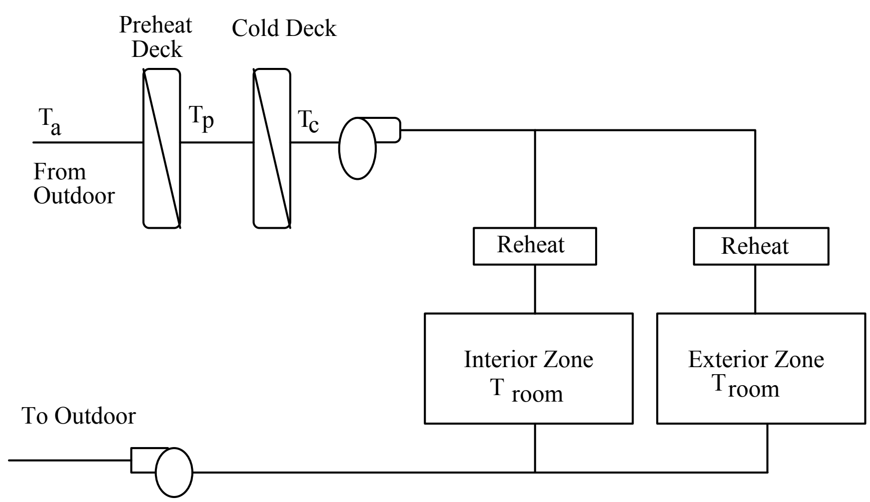


Figure 5-1: Schematic Diagram of Single Duct Air Handling Units

In addition to the single duct system that serves most of the building, there is one dual duct constant volume air handling unit, which provides cooling and heating to the library section. The design airflow is 27,000 cfm with 50% outside air intake. Figure 5-2 presents the schematic diagram of the dual duct air handling unit for the library section. The cold deck set point is 55°F. The hot deck set point varies from 85°F to 110°F as the outside air temperature decreases from 85°F to 40°F.

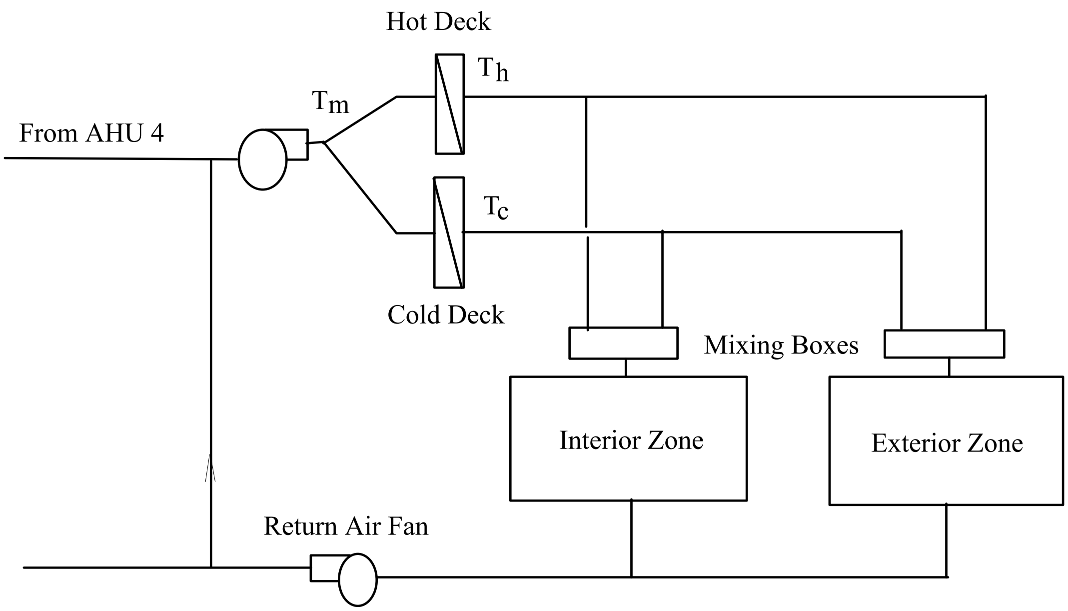


Figure 5-2: Schematic Diagram of Dual Duct Air Handling Unit for Library Section

Three single duct air handling units provide heating and cooling to mechanical rooms and other spaces. The design airflow is 14,000 cfm with 100% return air. Figure 5-3 presents the schematic diagram of these systems. The cold deck set point is 55°F. If the room temperature is satisfied, the AHUs will be turned off.

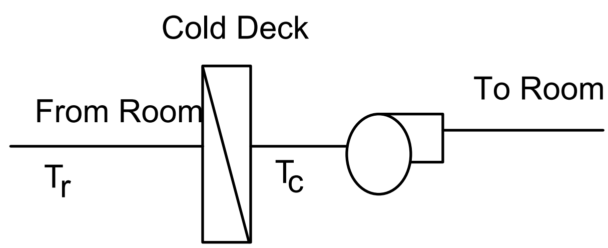


Figure 6-3: Schematic Diagram of Single Duct Air Handling Units for Mechanical Rooms

The building heating and cooling energy consumption are measured and recorded using a dedicated logger. The heating and cooling signals are split from utility meters. Figure 5-4 presents the measured hourly heating and cooling energy consumption versus the ambient temperature.

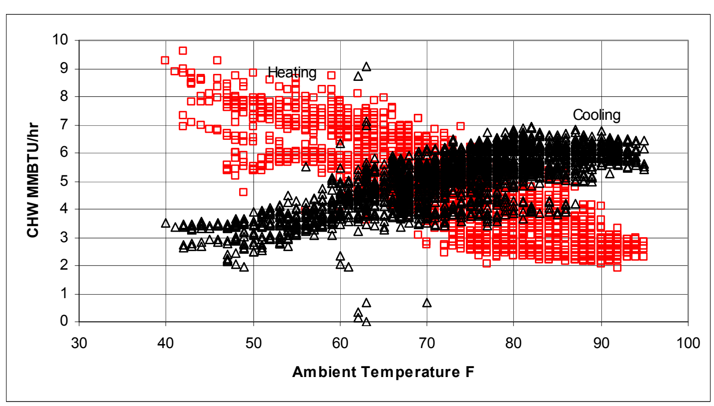


Figure 5-4: Measured Hourly Heating and Cooling Energy Consumption Versus the Ambient Temperature

Baseline Development

AirModel was used to simulate the building heating and cooling energy consumption using simplified building and system models. The building was divided into two parts: the laboratory section, which uses 100% outside air and the library section, which uses 50% outside air. Each part was simplified to two zones: interior and exterior. The design operational schedules were used in the simulation.

Figure 5-5 compares the measured heating and cooling with baseline heating and cooling energy consumption. The baseline energy consumption was simulated using actual Houston weather but not the weather data corresponding to the measured energy consumption, since the measured dew point temperature was missing for the measured energy consumption period. The baseline heating is significantly less than the measured heating while the baseline cooling is significantly higher than the measured cooling.

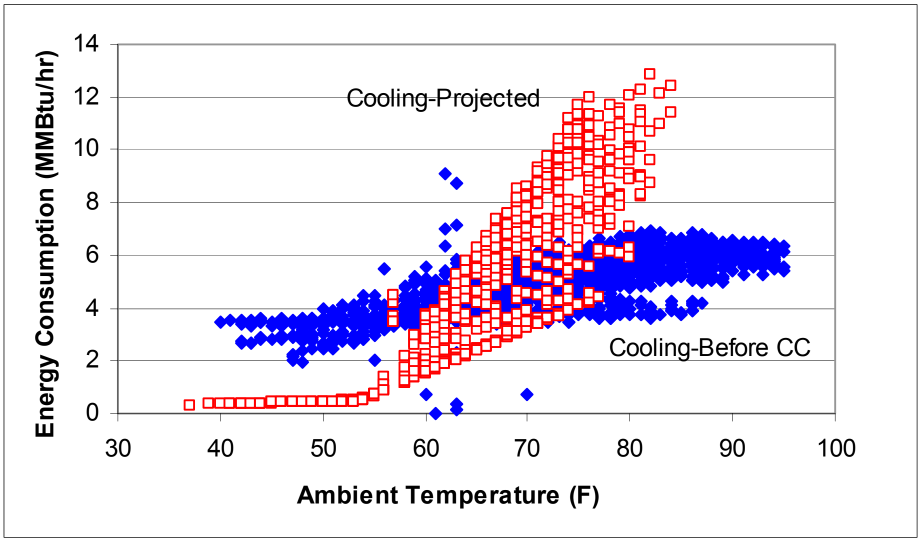


Figure 5-5a: Comparison of Baseline and Measured Cooling Energy Consumption

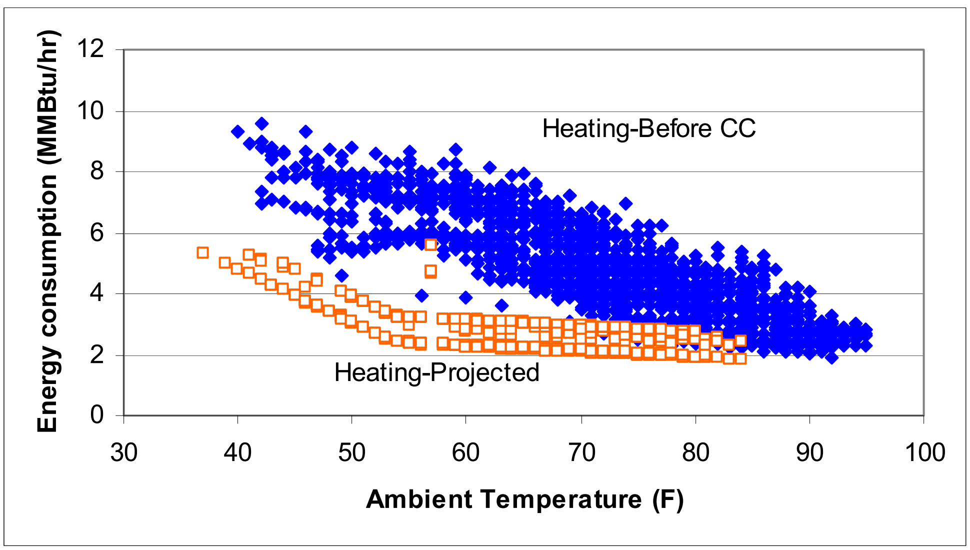


Figure 5-5a: Comparison of Baseline and Measured Cooling Energy Consumption

Fault Detection and Diagnosis

The baseline cooling is approximately twice as high as the measured values during the peak summer period while the baseline heating is slightly lower than the measured values during winter. This indicates that a fault may exist in the cooling energy metering system. Since the measured value is approximately 50% of the baseline, it was suggested that the scaling factor or the engineering conversion was set incorrectly. The measured cooling energy consumption is adjusted by a factor of 2. Figure 5-6 presents the corrected heating and cooling energy consumption.

Later, field inspection found that the by-pass line for the utility meter was fully open. Consequently, the utility meter only measured half of the chilled water flow.

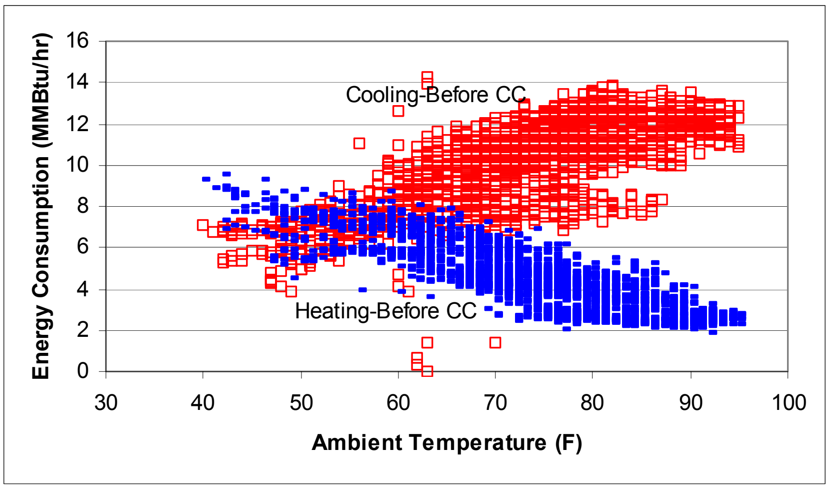


Figure 5-6: Measured Heating and Cooling Energy Consumption After Meter Correction

The difference between the measured and simulated cooling energy consumption decreases as the ambient temperature increases from 55°F to 95°F. The difference decreases when the ambient temperature decreases from 55°F to 30°F. This indicates a leaking chilled water valve. The leaking chilled water valve over-cooled the air. The terminal reheat-coils reheated the air to maintain room temperature, causing significant waste of heating and cooling energy.

Leaking chilled water flow can arise for a number of reasons. A recommendation was given to inspect the control valves.

Field Inspection

A field inspection was conducted and found that: (1) all control valves were less than 3 months old; (2) existing pneumatic lines were used when the valves were replaced; (3) all chilled water valves are normally open with a range of 3 to 8 psig; and (4) the maximum control pressure to the valves was 5 psig due to old, leaking pneumatic lines. As a result, it was not possible to close the valves fully.

This confirmed that the leaking chilled water control valves were the primary cause of the poor performance. Fixing the leaking pneumatic lines was expected to reduce the heating and cooling energy consumption to the baseline level.

Operational Optimization

It was suggested to reset the supply air temperature from 57°F to 59°F as the outside air temperature decreases 100°F to 59°F. This will decrease simultaneous heating and cooling significantly with a moderate room humidity level increase.

Implementation

The implementation included replacing the pneumatic lines and programming the reset schedule into the BAS system. These changes were made at the same time.

Figure 5-7 compares the measured chilled water consumption before fault detection and diagnosis, the chilled water consumption after fixing the pneumatic lines and implementing the optimized schedule, and the simulated optimal consumption. Figure 5-8 provides the same comparisons for heating water.

The measured annual cooling energy savings are 28,900 MMBtu/yr, and heating energy savings are 16,162 MMBtu/yr. The total annual cost savings are $369,000/yr, which includes heating savings of $129,000 and cooling savings of $240,000.

When the ambient temperature is lower than 50°F, the measured energy consumption agrees with the simulated energy consumption. When the ambient temperature is higher than 50°F, the measured energy consumption is somewhat higher than the simulated energy consumption. It appears that the building has other problems such as leaking reheat valves and excessive airflow.

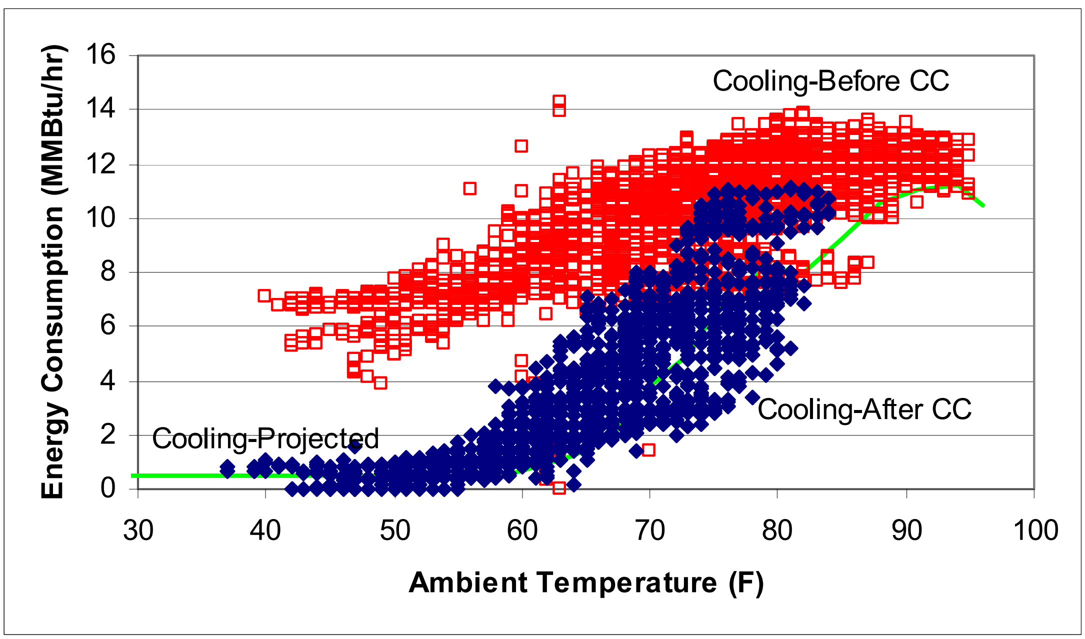


Figure 5-7: Comparison of Measured Cooling Energy Consumption Before and After Repair of Leaky Pneumatic Lines and Implementation of Optimal Reset Schedule

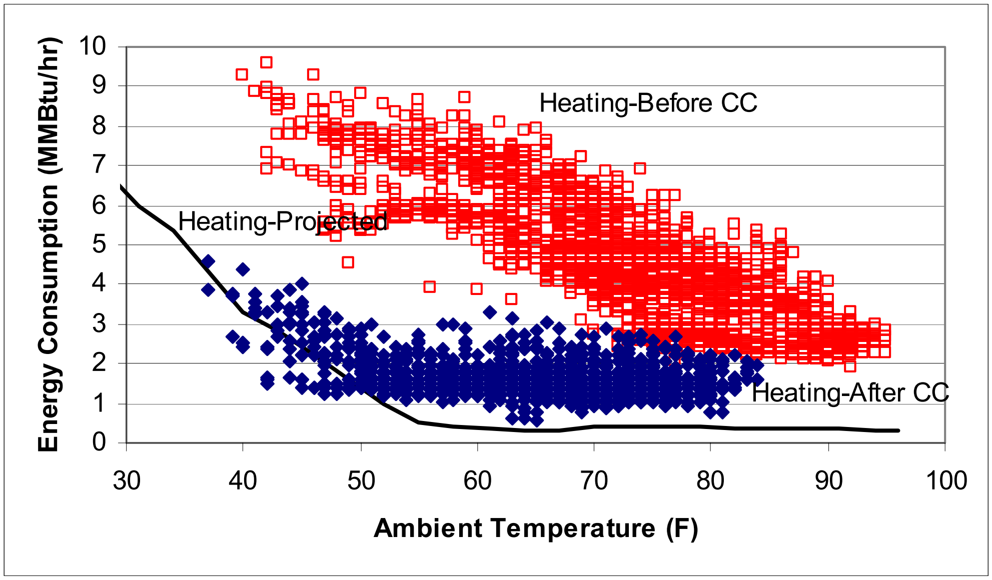


Figure 5-8: Comparison of Measured Heating Energy Consumption Before and After Repair of Leaky Pneumatic Lines and Implementation of Optimal Reset Schedule

Summary

The simulation effectively identified HVAC component problems and was used to develop optimized HVAC operation and control schedules in Case Study 1. Likewise, it identified the metering and valve leakage problems successfully in the second case. Re-heat valve leakage problems and excessive airflow problems were identified after fixing the leaking chilled water valve. This suggests that on-line fault detection should be an on-going process. The simulation indicated that building thermal energy consumption would be reduced by 23%, or $191,200/yr by using the optimized operating schedules in the building of Case Study 1. The measured energy savings were consistent with the simulated savings.

These results, coupled with similar experience in other buildings strongly support the potential value of on-line simulation as a diagnostic and optimization tool for building operation.

6. ASSESSMENT OF ONLINE SIMULATION FOR FAULT DETECTION AND DIAGNOSIS

Assessments were conducted for both AirModel and EnergyPlus. Since EnergyPlus has a more powerful simulation engine, it should have at least as much potential for use in online simulation as AirModel, providing it is equipped with proper interfaces. Therefore, two demonstration case studies were performed using AirModel for fault detection and diagnosis. One case involved a building with dual duct AHUs and the other a building with single duct AHUs.

General Assessment of AirModel

Since 1993, engineers from the Energy Systems Laboratories at Texas A&M University and the University of Nebraska, have been using AirModel for: (1) detection of energy inefficient operation; (2) diagnosis of inefficient operational schedules and major system faults, (3) development of improved operational schedules, (4) prediction of commissioning energy savings, and (5) as a baseline model for measurement of energy savings. Several papers have been published that discuss case studies and guidelines for use in these applications [Liu et al. 1994, Liu et al., 1995, Liu and Claridge 1995, Liu et al., 1997, Liu and Claridge, 1998, Wei et al. 1998, Giebler et al. 1998, Liu et al. 1998, Wei et al. 2000].

The experience documented in the case studies in the section to follow as well as others noted above indicates that Airmodel can detect energy problems that cause an approximate 5% increase in overall heating and/or cooling consumption. It can also be used to assist engineers in quickly diagnosing the actual mechanical and control system problems as illustrated in the case studies to follow.

AirModel can be used for on-line simulation through two approaches: parallel simulation or integrated simulation. For parallel simulation, AirModel will be installed in the central control system computer. AirModel will then be calibrated to represent the existing facility; an optimal control strategy is then developed and implemented in the calibrated model . The BAS system reports the key measured parameters, such as outside air temperature and relative humidity, heating energy, cooling energy, fan power, airflow rate, and room conditions. AirModel will simulate energy consumption and indoor conditions using the optimized calibrated inputs with BAS reported weather conditions. The measured and simulated energy consumption and indoor conditions will then be compared, and significant differences will be reported to the facility engineers or operators. Use of parallel simulation in the off-line mode (e.g. case studies referenced above) has resulted in approximately 20% reduction in energy use when compared with normal operating practices.

Due to its simplicity, AirModel could also be embedded in the BAS system. Modules of AirModel would receive the measured variables and simulate the energy consumption and room conditions. The comparison of measured data and simulated results could be performed in real time. This 'integrated' approach is best suited to individual system fault detection and diagnosis.

AirModel does have some deficiences for use in online simulation. It is robust in airside simulation but is less robust in waterside simulation and fault detection. Waterside modeling should be improved XX. It also uses simplified building load models generally making it unsuitable for detecting dynamic HVAC system or control problems.XX

General Assessment of EnergyPlus

EnergyPlus has essentially all the modeling capabilities of AirModel and hence should do the same job as AirModel for off-line fault detection if it is used properly. Currently, use of EnergyPlus requires more effort than AirModel, even for the same number of zones. This is due to lack of a suitable interface. However, this issue is now being addressed by third party software developers. It is expected that use of EnergyPlus for on-line simulation can potentially decrease building energy consumption by ~20% if the parallel procedure, mentioned above, is followed.

EnergyPlus may do a better job of dynamic fault detection and individual system fault detection since it uses dynamic load modeling. EnergyPlus also allows the user to specify output parameters.

EnergyPlus also has some deficiencies for use in online simulation. It is an energy balance based simulation program and does not simulate loop mechanical parameters, such as pressure loss. Because of this limitation, it is hard to detect some faults, such as excessive fan power due to an incorrect static pressure set-point. Because of the size and complexity of EnergyPlus, it is not suitable for use with the integrated approach for present BAS systems.

7. PLANS FOR FUTURE WORK

Two phase demonstration is planned. During the first phase, one or two commercial buildings will be selected. The building energy consumption and weather data will be measured in real time. AirModel will be run in parallel to the building operation. An interface will be developed to integrate the building automation system and AirModel input and output. Faults will be identified using discrepancies between the measured and simulated energy consumption. A manual of simulation based functional test procedures will be developed.

During the second phase, EnergyPlus will be used to identify building level faults as conducted in the first phase by AirModel. Currently, a number of system models are not developed for EnergyPlus. The AirModel program will be used to identify the system level faults, such as AHUs, chillers, and boilers. The potential and capabilities of the simulation based functional test will be documented based on the field application. A manual of fault diagnosis procedures will be developed for use with simulation programs.

To demonstrate the potential of simulation for fault detection, the procedures should be implemented in full scale buildings. It is planned to use the PKI Building at the University of Nebraska as the first demonstration site.

The PKI building is a 190,000 square-foot teaching and research building, located in Omaha, Nebraska. The Energy Systems Laboratory is located inside the PKI building. It was built in 1997 with a modern building automation system. It has 10 single duct variable air volume systems. The building has its own chiller and boiler plant.

The building was designed as an architectural engineering demonstration building. No ceiling tiles are installed in most portions of the building. All major mechanical and control devices can be directly observed and inspected.

During the design phase, the power distribution system was designed so that the electricity consumption can be measured for each major section and each major type. With a minimum metering investment (e.g. current transducers and pressure transducers), good quality data can be obtained to enhance the quality of fault detection.

8. REFERENCES

Crawley, D. B., L. K. Lawrie, C. O. Pedersen, F. C. Winkelmann, 2000. "EnergyPlus: Energy Simulation Program". *ASHRAE Journal*, Vol. 42, No. 4 (April), pp. 49-56.

ESRU, 2000. *The ESP-r System for Building Energy Simulation,* ESRU Manual U00/1, Energy Simulation Research Unit, University of Strathclyde, UK

Giebler, T., M. Liu, and D. E. Claridge, 1998, "Evaluation of Energy Conservation Measures by Model Simulation," *The Eleventh Symposium on Improving Building Systems in Hot and Humid Climates Proceedings*, June 1-2, Fort Worth, Texas.

http://www.eren.doe.gov/buildings/tools_directory/database

Kreider, J.F. and Haberl, J.S., 1994. "Predicting Hourly Building Energy Usage: The Great Predictor Shootout -- Overview and Discussion of Results", *ASHRAE Transactions*, Vol. 100, Pt. 2.

Lantern Corporation, 1990. *Voyager Data Exploration Software*, Clayton, MO.

LBNL, 1982. *DOE-2 Reference Manual*, Lawrence Berkeley Laboratory and Los Alamos National Laboratory, Report No. LBL-8706 Rev. 2.

Liu, M. J. Houcek, A. Athar, A. Reddy, D. E. Claridge, J. S. Haberl, 1994, "Identifying & Implementing Improved Operation & Maintenance (O&M) Opportunities in LoanSTAR Buildings," *Proceedings of 1994 ACEEE Summer Study*, Pacific Grove, CA. August 28 - September 3.

Liu, M. A. Athar, A. Reddy, D. E. Claridge, J. S. Haberl, and Ed. White, 1994. "Reducing Building Energy Costs Using Optimized Operation Strategies for Constant Volume Air Handling Systems," *Proceedings of Ninth Symposium on Improving Building Systems in Hot and Humid Climates,* Arlington, TX., May.

Liu, M. A. Athar, A. Reddy, D. E. Claridge, J. S. Haberl, and Ed. White, 1995, "Reducing Building Energy Costs Using Optimized Operation Strategies for Constant Volume Air Handling Systems," *ASHRAE Transactions-Symposia.* Volume 101, Part 2, pp. 688-700.

Liu, M and Claridge, D.E., 1995. "Application of Calibrated HVAC System Models to Identify Component Malfunctions and to Optimize Operation and Control Schedules", *Solar Engineering 1995 - Proceedings of the 1995 ASME/JSME/JSES International Solar Energy Conference*, Vol. 1, Maui, Hawaii, pp. 209-217, March 19-24.

Liu, Mingsheng, 1997. *User's Manual for Airside Simulation Program (AirModel)*, Energy Systems Laboratory, Texas A&M University.

Liu, M. and D.E. Claridge, 1998. "Use of Calibrated HVAC System Models to Optimize System Operation". *ASME Journal of Solar Energy Engineering*, Vol. 120, pp. 131-138.

Liu, M., and D. E. Claridge, 1998b. "Impacts of Optimized Cold & Hot Deck Reset Schedules on Dual Duct VAV Systems-Theory and Model Simulation." *The Eleventh Symposium on Improving Building Systems in Hot and Humid Climates Proceedings*, June 1-2, Fort Worth, Texas.

Liu, M., G. Wei, and D.E. Claridge, 1998. "Calibrating AHU Models Using Whole Building Cooling and Heating Energy Consumption Data", *Proceedings of the ACEEE 1998 Summer Study on Energy Efficiency in Buildings,* Volume 3, American Council for an Energy Efficient Economy, Washington, D.C., pp. 229-241.

Liu, M., M. Abbas, B. Veteto, and D. E. Claridge, 1998, "Impacts of Optimized Cold & Hot Deck Reset Schedules On Dual Duct VAV System-Application and Results." *The Eleventh Symposium on Improving Building Systems in Hot and Humid Climates Proceedings*, June 1-2, Fort Worth, Texas.

Liu, M., D. E. Claridge, 1999, "The Maximum Potential Energy Savings from Optimizing Cold and Hot Deck Reset Schedules for Dual Duct VAV Systems." *Journal of Solar Energy Engineering*, Vol. 121, pp. 171-175.

Wei, G., M. Liu, and D. E. Claridge, 1998, "Signatures of Heating and Cooling Energy Consumption for Typical AHUs," *The Eleventh Symposium on Improving Building Systems in Hot and Humid Climates Proceedings*, June 1-2, Fort Worth, Texas.

APPENDIX A: SIMULATION PROGRAMS

This appendix provides summary descriptions of the 15 programs listed in the table below.

		Detailed general purpose detailed whole building energy simulation programs
1	APACHE	thermal design, thermal analysis, energy simulation, dynamic simulation, system simulation
2	BLAST	energy performance, design, retrofit, research, residential and commercial buildings
3	DOE-2	energy performance, design, retrofit, research, residential and commercial buildings
4	EnergyPlus	energy simulation, load calculation, building performance, simulation, energy performance, heat balance, mass balance
5	HAP v4.0	energy performance, load calculation, energy simulation, HVAC equipment sizing
6	TRACE 700	energy performance, load calculation, HVAC equipment sizing, energy simulation, commercial buildings
7	VisualDOE	energy performance, design, retrofit, research, residential and commercial buildings
		Simplified general purpose whole building energy simulation programs
1	ASEAM	energy performance, existing buildings, commercial buildings
2	System Analyzer	energy analyses, load calculation, comparison of system and equipment alternatives
		Specialized building energy simulation programs
1	HBLC	heating and cooling loads, heat balance, energy performance, design, retrofit, residential and commercial buildings
2	HVACSIM+	HVAC equipment, systems, controls, EMCS, complex systems
3	SPARK	object-oriented, research, complex systems, energy performance
4	TRNSYS	design, retrofit, research, energy performance, complex systems, commercial buildings
		Data visualization/analysis programs
1	ENFORMA	data acquisition, energy performance, building diagnostics, HVAC systems, lighting systems
2	Visualize-IT Energy Information and Analysis Tool	energy analysis, rate comparison, load profiles, interval data

The information provided in this appendix is taken from the DOE web page for all programs described. AirModel is not shown on the DOE web page, so the program description is given only in the main text. This information can be found at: http://www.eren.doe.gov/buildings/tools_directory/database

ASEAM

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

Evaluation of high-potential, cost effective energy efficiency projects in existing Federal buildings; calculates results that are within 4-5% of DOE-2 annual energy results; using quick input routines, permits evaluation of a 10,000 ft2 building in about ten minutes. ASEAM (A Simplified Energy Analysis Method) Version 5.0 automatically creates DOE-2 input files. The FEMP Architects and Engineers Guide to Energy Conservation in Existing Buildings (published November 1990) uses ASEAM as a primary example of how software can be used in over 180 retrofit projects.

Keywords: energy performance, existing buildings, commercial buildings

Expertise Required: Designed to be used by non-engineers with minimal training.

Users: Several hundred.

Audience: Federal energy personnel.

Input: Building type and location, outside dimensions, percent glazing, usage patterns, number of floors, central systems and plant.

Output: Average monthly and annual energy savings from retrofits, taking into account all interactive effects using parametric analysis for optimization.

Computer Platform: PC-compatible, 286 minimum, with math coprocessor preferred.

Programming Language: C

Strengths: Currently allows an engineer to easily perform very sophisticated whole building energy analysis (calibrates to utility data using Lotus macros, does parametric analysis on dozens of energy conservation opportunities).

Weaknesses: Should have the same analytical process fully automated for less sophisticated users.

BLAST

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

Performs hourly simulations of buildings, air handling systems, and central plant equipment in order to provide mechanical, energy and architectural engineers with accurate estimates of a building's energy needs. The zone models of BLAST (Building Loads Analysis and System Thermodynamics), which are based on the fundamental heat balance method, are the industry standard for heating and cooling load calculations. BLAST output may be utilized in conjunction with the LCCID (Life Cycle Cost in Design) program to perform an economic analysis of the building/system/plant design.

Keywords: energy performance, design, retrofit, research, residential and commercial buildings

Expertise Required: High level of computer literacy not required; engineering background helpful for analysis of air handling systems.

Users: Over 500.

Audience: Mechanical, energy, and architectural engineers working for architect/engineer firms, consulting firms, utilities, federal agencies, research universities, and research laboratories.

Input: Building geometry, thermal characteristics, internal loads and schedules, heating and cooling equipment and system characteristics. Readable, structured input file may be generated by HBLC (Windows) or the BTEXT program.

Output: More than 50 user-selected, formatted reports printed directly by BLAST; also the REPORT WRITER program can generate tables or spreadsheet-ready files for over one hundred BLAST variables.

Computer Platform: PC-compatible, 386 or higher; HP/Apollo. Source code is available and has been successfully compiled on most UNIX workstations.

Programming Language: FORTRAN

Strengths: PC Format has Windows interface as well as structured text interface; detailed heat balance algorithms allow for analysis of thermal comfort, passive solar structures, high and low intensity radiant heat, moisture, and variable heat transfer coefficients -- none of which can be analyzed in programs with less rigorous zone models.

Weaknesses: High level of expertise required to develop custom system and plant models.

DOE-2

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

Hourly, whole-building energy analysis program calculating energy performance and life-cycle cost of operation. Can be used to analyze energy efficiency of given designs or efficiency of new technologies. Other uses include utility demand-side management and rebate programs, development and implementation of energy efficiency standards and compliance certification, and training new corps of energy-efficiency conscious building professionals in architecture and engineering schools.

Keywords: energy performance, design, retrofit, research, residential and commercial buildings

Expertise Required: Recommend 3 days of formal training in basic and advanced DOE-2 use.

Users: 800 user organizations in U.S., 200 user organizations internationally; user organizations consist of 1 to 20 or more individuals.

Audience: Architects, engineers in private A-E firms, energy consultants, building technology researchers, utility companies, state and federal agencies, university schools of architecture and engineering.

Input: Hourly weather file plus Building Description Language input describing geographic location and building orientation, building materials and envelope components (walls, windows, shading surfaces, etc.), operating schedules, HVAC equipment and controls, utility rate schedule, building component costs. Available with a range of user interfaces, from text-based to interactive/graphical windows-based environments.

Output: 20 user-selectable input verification reports; 50 user-selectable monthly/annual summary reports; user-configurable hourly reports of 700 different building energy variables.

Computer Platform: PC-compatible; Sun; DEC-VAX; DECstation; IBM RS 6000; NeXT; 4 megabytes of RAM; math coprocessor; compatible with Windows, UNIX, DOS, VMS.

Programming Language: FORTRAN 77

Strengths: Detailed, hourly, whole-building energy analysis of multiple zones in buildings of complex design; widely recognized as the industry standard.

Weaknesses: High level of user knowledge.

EnergyPlus

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

A new generation building energy simulation program that builds on the most popular features and capabilities of BLAST and DOE-2. EnergyPlus will include innovative simulation capabilities including time steps of less than an hour, modular systems simulation modules that are integrated with a heat balance-based zone simulation, and input and output data structures tailored to facilitate third party interface development. Other planned simulation capabilities include solar thermal, multizone air flow, and electric power simulation including photovoltaic systems and fuel cells.

Keywords: energy simulation, load calculation, building performance, simulation, energy performance, heat balance, mass balance

Expertise Required: High level of computer literacy not required; engineering background helpful for analysis portions.

Users: Over 500.

Audience: Mechanical, energy, and architectural engineers working for architect/engineer firms, consulting firms, utilities, federal agencies, research universities, and research laboratories.

Input: Basic EnergyPlus program (current release is Beta 4 of 5 betas) will have a simple ASCII input file. It is envisioned that private developers will wish to develop more targeted / domain specific user interfaces.

Output: Basic EnergyPlus program will have several simple ASCII output files - readily adapted into spreadsheet form for further analysis.

Computer Platform: Emphasis on platform portability. Windows 9x/NT/2000 executable will be available. Has been successfully compiled on UNIX and Linux platforms.

Programming Language: Fortran 90

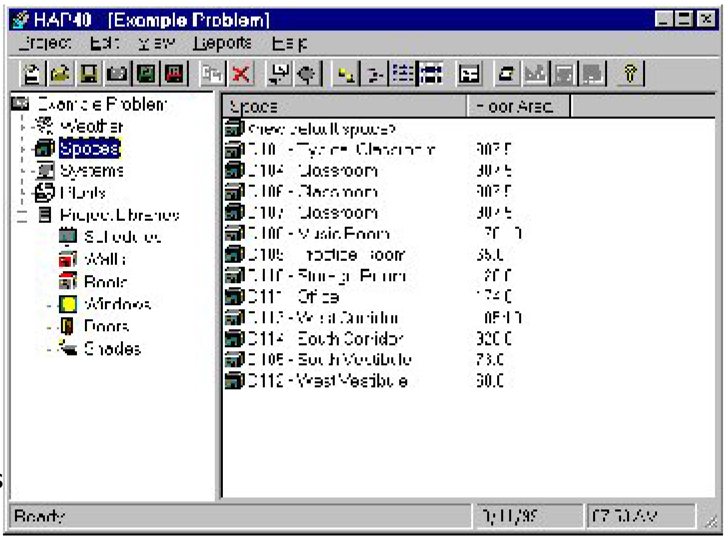
Strengths: Accurate, detailed simulation capabilities through complex modeling capabilities. Input is geared to the 'object' model way of thinking. Successful interfacing using IFC standard architectural model has been demostrated. Extensive testing (comparing to available test suites) is being done during development and results will be available.

Weaknesses: Difficult to use without graphical interfaces.

Validation/Testing: EnergyPlus has been tested against the IEA BESTest building load and HVAC tests. Results are available under Testing and Validation on the

HAP V4.0

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database



A versatile system design tool and a powerful energy simulation tool in one package. HAP (Hourly Analysis Program) v4.0 for Windows also provides the ease of use of a Windows-based graphical user interface, and the computing power of Windows 32-bit software.

HAP's design module uses a system-based approach which tailors sizing procedures and reports to the specific type of system being considered. Central AHUs, packaged rooftop units, split systems, fan coils and PTACs can easily be designed, as can CAV, VAV, single and multiple-zone systems. The ASHRAE-endorsed Transfer Function Method is used to calculate building heat flow.

HAP's energy simulation module performs a true 8760 hour energy simulation of building heat flow and equipment performance. It uses TMY weather data and the Transfer Function Method. Many types of air handling systems, packaged equipment, and plant equipment can be simulated. Costs can be computed using complex utility rates. Extensive, easy to read reports and graphs document hourly, daily, monthly and annual energy and cost performance.

Keywords: energy performance, load calculation, energy simulation, HVAC equipment sizing

Expertise Required: General knowledge of HVAC engineering principles.

Users: 5000 worldwide.

Audience: Practicing engineers involved in the design, specification and analysis of commercial HVAC systems/equipment. Instructional tool in colleges and universities. Design/build contractors, HVAC contractors, facility engineers and other professionals involved in the design and analysis of commercial building HVAC systems. It can be used for new design, retrofit and energy conservation work.

Input: Building geometry, envelope assemblies, internal heat gains and their schedules; equipment components, configurations, controls and efficiencies; utility rates.

Output: 48 design and analysis reports available to view or print. Design reports provide system sizing information, check figures, component loads, and building temperatures. Simulation reports provide hourly, daily, monthly and annual performance data. Users control the content and format of all graphical reports.

Computer Platform: Windows 95/98/NT compatible PC, Pentium or higher, minimum 32MB RAM, minimum 20 MB hard disk space.

Programming Language: Software is compiled. Source code is not available.

Strengths: HAP balances ease of use with technical sophistication. Technical features are comparable to DOE 2.1; comparison studies with DOE 2.1 have yielded good correlation. The Windows graphical user interface, report features, data management features, on-line help system and printed documentation combine to provide an efficient, easy to use tool.

Weaknesses: HAP is not an effective tool for the research scientist. Because it is designed for the practicing engineer, HAP does not permit modification of source code to model one-of-a-kind equipment configurations and control schemes often studied in research situations.

SPARK

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

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An object-oriented program that allows the user to quickly build models of complex physical processes by connecting equation-based calculation modules from an object library. SPARK (Simulation Problem Analysis and Research Kernel) creates an executable simulation program from this network ready to be run.

See example screen images

Keywords: object-oriented, research, complex systems, energy performance

Expertise Required: High level of computer literacy required.

Users: 50

Audience: Building technology researchers and energy consultants.

Input: Calculation modules created symbolically or selected from a library, then connected using a Graphical Editor or Network Specification Language; run-time input such as time step and parameter values.

Output: Graphical display of results for any simulation variable.

Computer Platform: Windows 95/98/NT, Sun Unix, Linux, HP

Programming Language: C, C++

Strengths: Capable of modeling complex building envelopes and building HVAC systems to any level of detail; built-in problem decomposition and reduction techniques give execution times that are 10-20 times faster than similar programs. User-selectable time step allows modeling short time-step dynamics; symbolic input of equations avoids programming; Graphical Editor simplifies model description and construction of customized networks; library of HVAC components and systems.

Weaknesses: High level of user expertise in system being modeled required.

System Analyzer

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

Software package for load calculation and energy and economic comparative analysis. System Analyzer permits a quick evaluation of virtually any building, system, and equipment combination. Thus, it can be used either as a scoping tool to decide what systems may be appropriate for an initial design, or to get a general feeling of how one system/equipment combination may perform over another. If a certain combination seems especially promising, further analysis can be done by exporting inputs into TRACE 600. The possibilities are endless. And since the program is Windows-based, virtually anyone with minimal HVAC training and experience can use it.

Keywords: Energy analyses, load calculation, comparison of system and equipment alternatives

Expertise Required: Basic knowledge of HVAC equipment, systems and terms.

Users: Approximately 800 users worldwide.

Audience: Utility companies and ESCOs who wish to promote alternative cooling strategies; architects and marketing persons who may use this as a powerful, interactive presentation tool; and mechanical engineers who design, size and calculate energy consumption for HVAC systems.

Input: Building design parameters, system configurations and utility rates.

Output: Print any of the 30 design and analysis reports and graphs such as building loads, equipment energy consumption, economic analysis, yearly cash flows and monthly building load profiles for comparisons or presentations.

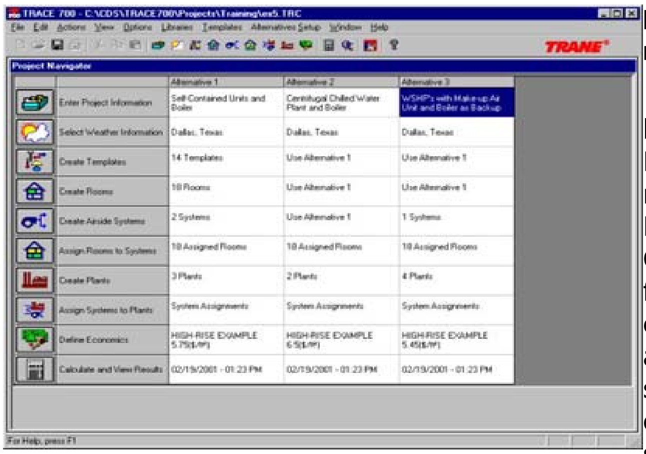
Computer Platform: PC-compatible 486 or higher (Pentium recommended), Windows 3.1 or higher, 12 MB RAM (16 MB recommended); 13 MB free hard disk space.

Programming Language: CA-Realizer

Strengths: System Analyzer is a powerful, interactive presentation tool and it's graphical interface allows even a beginner with minimal HVAC experience to get a complete energy and economic analysis in as little as 10 minutes. The graphs, when printed on a color printer, provide powerful visual proof for proposals to justify better HVAC systems.

Weaknesses: The program provides reliable comparative system analyses, but lacks some of the extensive details of load and energy components available in the TRACE suite.

TRACE 700



Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

Trane's **TRACE™ 700** software - the latest version of Trane Air Conditioning Economics - brings the algorithms recommended by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) to the familiar Microsoft® Windows® operating environment. Use it to assess the energy and economic impacts of building-related selections such as architectural features, comfort-system design, HVAC equipment selections, operating schedules, and financial options.

Flexible data entry, coupled with multiple views and "drag-and-drop" load assignments, simplify the modeling process and help you identify optimal zoning and plant configurations. Compare up to four alternatives for a single project by modeling various air distribution and mechanical system/control options; then assess the life-cycle cost and payback of each combination based on 8,760 hours of operation... without investing lots of extra time.

Templates provide a fast, easy way to analyze the effects of changes in building loads such as airflows, thermostat settings, occupancy, and construction. An extensive library of construction materials, equipment, and weather profiles (nearly 500 locations) enhances the speed and accuracy of your analyses. Choose from seven different ASHRAE cooling and heating methodologies, including the Exact Transfer Function.

See example screen images

Keywords: Energy performance, load calculation, HVAC equipment sizing, energy simulation, commercial buildings

Expertise Required: General knowledge of HVAC engineering principles, building geometry, and the Microsoft Windows operating system

Users: Approximately 1,200 worldwide, including single and site/LAN licenses

Audience: Engineers, architects, and contractors who design and analyze commercial HVAC systems/equipment for new and existing buildings; also energy consultants and utility companies; building technology researchers; state and federal agencies; colleges and universities

Input: Building design parameters; operating schedules; HVAC system configurations, equipment types, and control strategies; utility rates

Output: Display, print, graph, or export any of 54 monthly/yearly summary reports and hourly analyses, including system "checksums," psychrometric state points, peak cooling/heating loads, building envelope loads, building temperature profiles, equipment energy consumption, and ASHRAE 90 analysis

Computer Platform: Personal computer with a Pentium® 233 or higher processor, Microsoft Windows 95/98/2000/ME/NT operating system, 128 megabytes (MB) of RAM, 80 MB of free hard disk space, Super VGA display, CD-ROM drive, and a Microsoft-compatible pointing device

Programming Language: Microsoft® Visual C++ development system

Strengths: Models 30 different airside systems, plus many HVAC plant configurations and control strategies, including thermal storage, cogeneration, and fan-pressure optimization. Customizable libraries and templates simplify data entry and allow greater modeling accuracy. Documentation includes detailed online Help and a printed modeling guide. Experienced HVAC engineers and support specialists provide free technical support.

Weaknesses: Formal training is recommended for new users (Visit our Web site for training options.)

TRNSYS

Description below taken from
http://www.eren.doe.gov/buildings/tools_directory/database

Modular system simulation software; includes many of the components commonly found in thermal energy systems as well as component routines to handle input of weather or other time-dependent forcing functions and output of simulation results. TRNSYS (TRaNsient SYstem Simulation Program) is typically used for HVAC analysis and sizing, solar design, building thermal performance, analysis of control schemes, etc.

Keywords: design, retrofit, research, energy performance, complex systems, commercial buildings

Expertise Required: None to use standard package; FORTRAN knowledge helpful for developing new components

Users: 1000 US; 2000 worldwide.

Audience: Engineers, researchers, architects.

Input: TRNSYS input file, including building input description, characteristics of system components and manner in which components are interconnected, and separate weather data (supplied with program). Input file can be generated by graphically connecting components.

Output: Life cycle costs; monthly summaries; annual results; histograms; plotting of desired variables (by time unit); online variable plotting (as the simulation progresses).

Computer Platform: Windows 95 and NT for TRNSYS interface programs. (Distributed source code will compile and run on any Fortran platform).

Programming Language: FORTRAN (although unnecessary for the use of standard components).

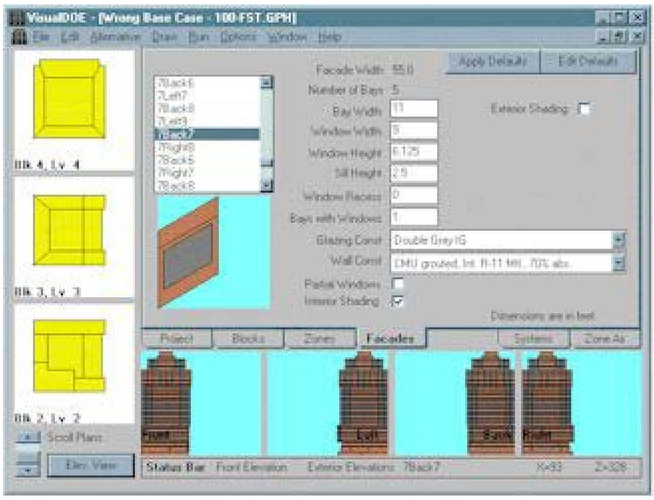
Strengths: Due to its modular approach, extremely flexible for modeling a variety of thermal systems in differing levels of complexity; supplied source code and documentation provide an easy method for users to modify or add components not in the standard library; extensive documentation on component routines, including explanation, background, typical uses and governing equations; supplied time step, starting and stopping times allowing choice of modeling periods. Version 14.2 moves all the TRNSYS utility programs to the MS Windows platform (95/NT), including a choice of graphical drag-and-drop programs for creating input files, a utility for easily creating a building input file, and a program for building TRNSYS-based applications for distribution to non-users. Web-based library of additional components and frequent downloadable updates are also available to users.

Weaknesses: No assumptions about the building or system are made (although default information is available) so the user must have detailed information about the building and system and enter this information into the TRNSYS interface.

VisualDOE

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

Windows interface to the DOE-2.1E energy simulation program. Through the graphical interface, users construct a model of the building's geometry using standard block shapes or using a built-in drawing tool. Building systems are defined through a point-and-click interface. A library of constructions, systems and operating schedules is included, and the user can add custom elements as well. If desired, the program assigns default values for parameters based on the vintage and size of the building.



VisualDOE is especially useful for studies of envelope and HVAC design alternatives. Up to 20 alternatives can be defined for a single project. Summary reports and graphs may be printed directly from the program. Hourly reports of building parameters may also be viewed.

Keywords: energy performance, design, retrofit, research, residential and commercial buildings

Expertise Required: Basic experience with Windows programs is important. Familiarity with building systems is desirable but not absolutely necessary. One to two days of training is also desirable but not necessary for those familiar with building modeling.

Users: 300+, US and international.

Audience: Building designers (new and retrofit), researchers, equipment and utility marketers.

Input: Assigns default values to many of the inputs based on the building vintage and size. Required inputs include floorplan, occupancy type, and location. These are all that is required to run a simulation. Typically, however, inputs include wall, roof and floor constructions; window area and type; HVAC system type and parameters; and lighting and office equipment power.

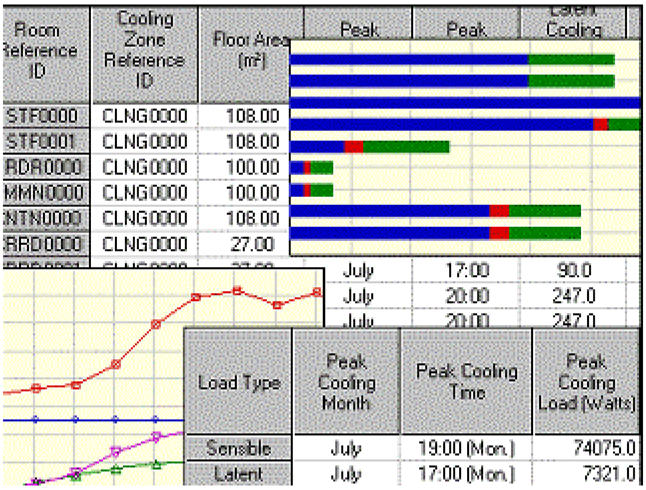
Output: Produces input and output summary reports that may be viewed on-screen or printed. A number of graphs may be viewed and printed. These graphs can compare selected alternatives and/or selected hourly variables. Standard DOE-2.1E reports may be selected.

Computer Platform: Windows 3.1, Windows 95, or Windows NT. 486 or better, 8MB+ RAM, 30MB hard drive space.

Programming Language: Visual Basic and Visual C++

Strengths: Allows rapid development of energy simulations, dramatically reducing the time required to build a DOE-2 model. Specifying the building geometry is much faster than other comparable software, making VisualDOE useful for schematic design studies of the building envelope or HVAC systems. Uses DOE-2 as the simulation engine--an industry standard that has been shown to be accurate; implements DOE-2's daylighting calculations; allows input in SI or IP units; imports CADD data to define thermal zones. For advanced users, allows editing of equipment performance curves. Displays a 3D image of the model to help verify accuracy. Allows simple management of up to 20 design alternatives. Experienced DOE-2 users can use VisualDOE to create input files, modify them, and run them from within the program.

Weaknesses: Passive solar models may not be too accurate. Natural ventilation modeling is limited to a specified air changes per hour (ACH) that may be scheduled on or off. Underground buildings must be modeled with exterior walls, although custom constructions can be entered to represent the mass of the earth. Underfloor air distribution systems may provide benefits that are not directly modeled in DOE-2. For instance, DOE-2 does not account for thermal stratification in a space. Version 2.5 of VisualDOE does not support modeling of skylights.



APACHE

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

Software tool for thermal design & energy simulation related to buildings. In design mode, APACHE covers the calculation of heating, cooling and latent room loads, the sizing of room units, internal comfort analysis and codes/standards checks. In simulation mode, APACHE performs a dynamic thermal simulation using hourly weather data. Linked modules deal with the performance of HVAC plant and natural ventilation. APACHE is a component of the IES Virtual Environment, an integrated computing environment encompassing a wide range of tasks in building design.

Applications:

- Thermal design (heating, cooling & latent load calculations)
- Equipment sizing
- Codes & standards checks
- Dynamic building thermal performance analysis
- Systems and controls performance
- Energy use

Modules:

- Geometrical modelling, building data input & visualisation
- Management of data relating to materials, occupancy, plant operation and climate.
- Shading analysis
- Heat Gain calculations
- Heat Loss calculations
- Dynamic thermal simulation
- Natural ventilation & indoor air quality analysis
- HVAC system simulation
- Results presentation & analysis

Keywords: thermal design, thernal analysis, energy simulation, dynamic simulation, system simulation

Expertise Required: 2 days training is recommended for the basic modules, with additional courses available for specific applications. Available in UK and other countries by arrangement.

Users: Many throughout Europe.

Audience: mechanical building services engineers, local government, building managers & landlords, building design consultants, architects, and university research and teaching departments.

Input: Geometrical building data may be imported from a range of CAD systems via customised links or DXF files. Geometrical models may alternatively be entered using facilities within the Virtual Environment. Input of data relating to materials, occupancy, internal gains, climate, air movement and systems is managed via graphical interfaces and supported by extensive databases.

Output: APACHE presents a wide range of outputs in tabular and graphical form. Outputs may be exported in a variety of common formats.

Computer Platform: PC running Windows 95, 98 or NT (3.51 or higher). 100 MB Ram or paging disk. 100 MB disk space. CD-Rom drive.

Programming Language: Visual Basic, C++, Fortran 77

Strengths: Operates within an integrated computing environment covering a range of building analysis functions. Strong links with CAD. Undergoing rapid development, with continuing input from research and engineering practice. Supported by in-house expertise. Rigorous analysis and visualisation of shading and solar penetration. Flexible & versatile system HVAC and controls modelling. Integrated simulation of building and HVAC systems.

Weaknesses: Certain energy systems not covered currently, eg phase-change materials, roof ponds.

HBLC

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

Powerful software tool for calculating heating and cooling loads for buildings. Allows the user to access complex heat-balance algorithms using a Windows interface. Geometric inputs are entered graphically using intuitive click-and-drag mouse functions and allows the user to visualize the building model as it is developed. HBLC (Heat Balance Loads Calculator) creates an input file for and runs the BLAST (Building Loads Analysis and System Thermodynamics) simulation program. After simulating, HBLC retrieves results from the simulation and can present these results in a graphical presentation. On-line helps provide valuable on-the-spot assistance that will benefit both new and experienced users. HBLC is an excellent tool which will make the process of developing BLAST input files more intuitive and efficient.

Keywords: heating and cooling loads, heat balance, energy performance, design, retrofit, residential and commercial buildings

Expertise Required: High level of computer literacy not required; engineering background helpful for analysis portions.

Users: Over 500.

Audience: Mechanical, energy, and architectural engineers working for architect/engineer firms, consulting firms, utilities, federal agencies, research universities, and research laboratories.

Input: Interactive program in Windows environment.

Output: Can access most of BLAST's features. Presents graphs, for example, individual zone loads, load splits, etc.

Computer Platform: Windows 95 or NT preferred – may be able to use Windows 3.1 environment.

Programming Language: Visual Basic

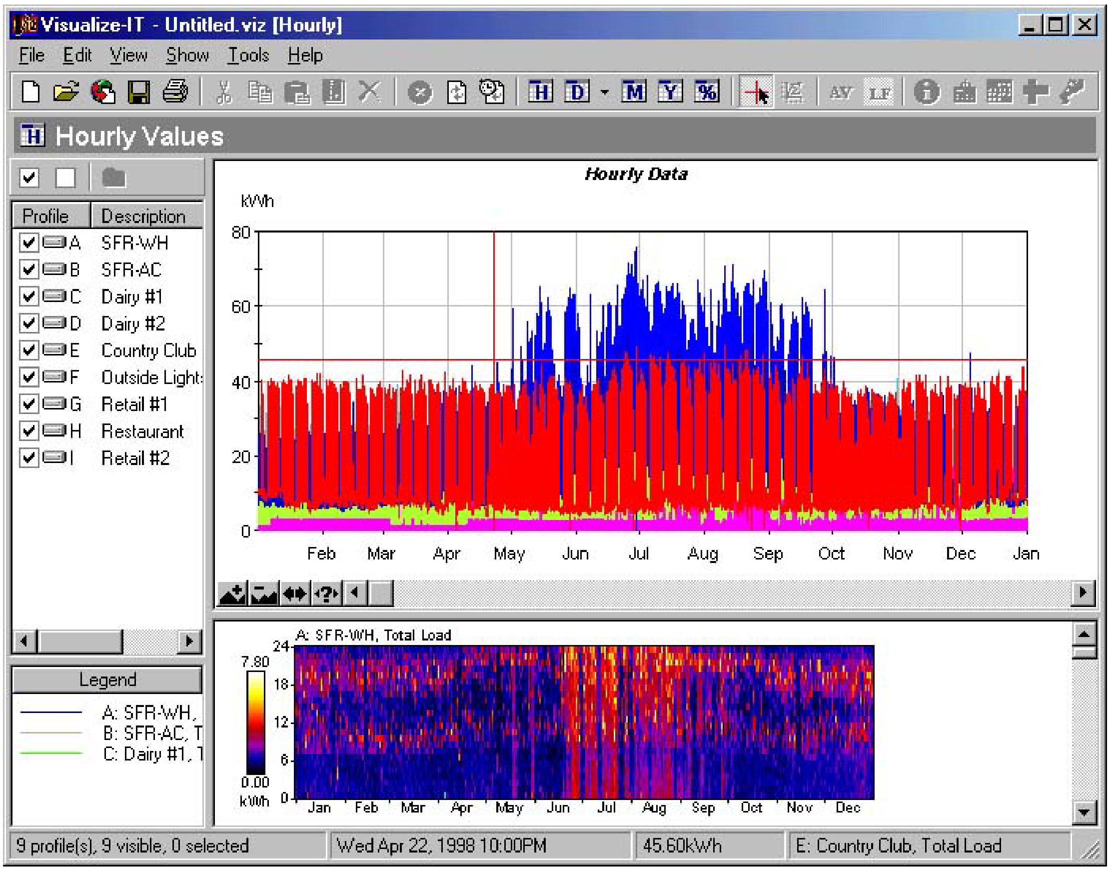
Strengths: Input allows for easy detailing of geometric building model. Access to complex, accurate BLAST models as well as simple presentation of results. Access to all the BLAST libraries and these can be customized to user needs. Customization of necessary Fan System and Plant parameters for the described facility. Context sensitive help for HBLC features. Access to all the BLAST Family of Programs through the HBLC interface. Access to the BLAST Manual (Help file) from within HBLC.

Weaknesses: Some features of BLAST's geometry are not available through this interface.

Visualize-IT Energy Information and Analysis Tool

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

Designed to explore, summarize and analyze time series interval data. Visualize-IT has been developed specifically for electric and gas load data, but it is equally useful as a general purpose data visualization tool for other time series measurements such as weather, industrial process control, and water quality.



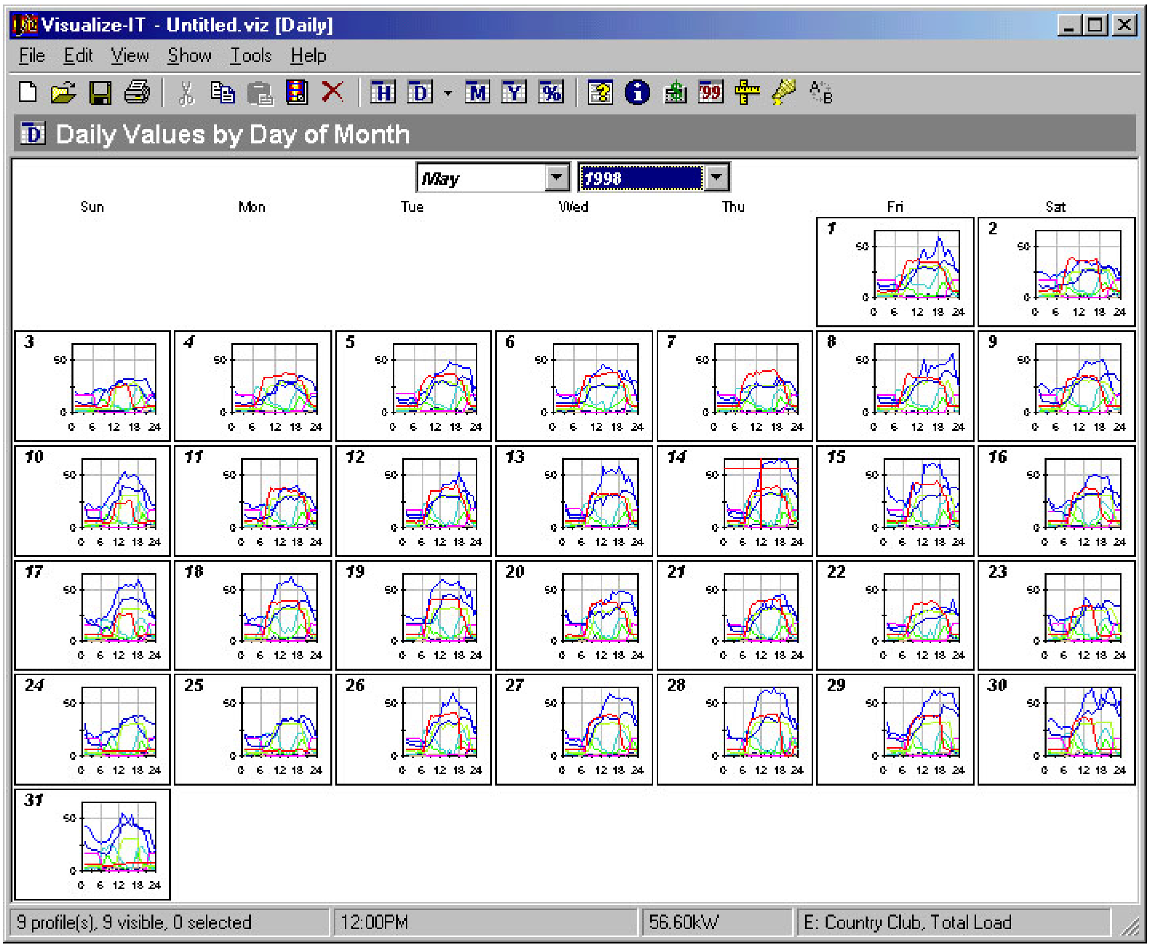
Keywords: energy analysis, rate comparison, load profiles, interval data

Expertise Required: Basic knowledge of energy data analysis and concepts.

Users: Over 100 users internationally.

Audience: Load Researchers, Building Simulation Engineers, Facilities Managers, Energy Account Managers.

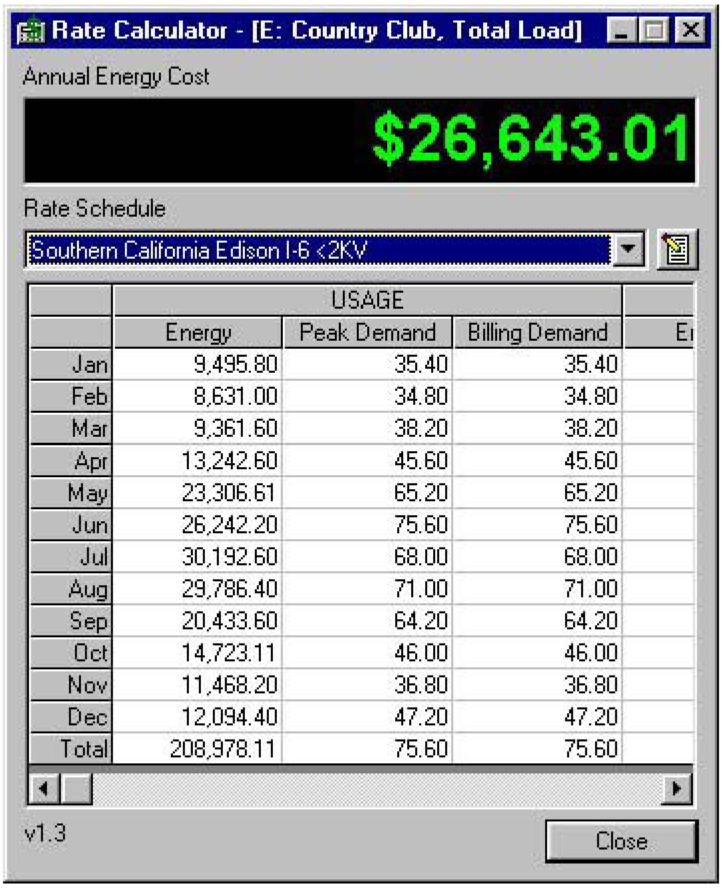
Input: Any type of interval (primarily load) data. Visualize-IT can analyze other types of interval data such as weather, hourly prices, etc. Data formats which are supported are Text, CSV, Binary, DOE-2.1E output files, MV-90 and Loadstar Output files, and real-time data downloaded directly from a number of internet data providers.



Output: Visualize-IT produces numerous interactive charts and Energy Prints, a color map of interval data, with the time of day plotted on the Y axis, the day plotted on the X axis, and the measured value for each interval represented using color. Charting options include: Raw values, Aggregated values (by day, week, month, billing period, etc.), Day Profiles (Average Weekday, Weekend, etc.), Calendar view, Frequency Distribution and Cumulative Distribution (Load Duration) graphs. Various tools operate on the data to scale or true-up profiles, restrict analysis to particular time periods, and provide many other operations. The optional Rate Calculator provides a wizard used to design and analyze rate schedules and energy bills. Data (and graphs) can be copied and pasted directly into other applications. Visualize-IT supports a number of standard export formats as well.

Computer Platform: Windows 95/98/ME/NT and 2000

Programming Language: Visual Basic and C++



	USAGE			
	Energy	Peak Demand	Billing Demand	En
Jan	9,495.80	35.40	35.40	
Feb	8,631.00	34.80	34.80	
Mar	9,361.60	38.20	38.20	
Apr	13,242.60	45.60	45.60	
May	23,306.61	65.20	65.20	
Jun	26,242.20	75.60	75.60	
Jul	30,192.60	68.00	68.00	
Aug	29,786.40	71.00	71.00	
Sep	20,433.60	64.20	64.20	
Oct	14,723.11	46.00	46.00	
Nov	11,468.20	36.80	36.80	
Dec	12,094.40	47.20	47.20	
Total	208,978.11	75.60	75.60	

Strengths: Data visualization, rate analysis, ability to analyze and compare data with different sample rates, units, time periods and from any number of sources simultaneously.

Weaknesses: Not easily suited to analyzing data with sample rates greater than 1 hour (i.e., daily or monthly data).

Validation/Testing: N/A

ENFORMA

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

Includes the MicroDataLogger portable data acquisition equipment and HVAC and Lighting Analyzer software. ENFORMA is designed to cost-effectively gather data and convert it into information about building performance. ENFORMA provides a unique solution that can gather the data at a minimal cost and help you determine solutions to typical building problems. This detailed diagnostic information is the key that allows you to improve upon your current services or expand into new business opportunities. ENFORMA solutions typically result in projects with paybacks of less than one year.

ENFORMA solutions can help you improve upon or begin doing the following services: Performance Guarantees, Comfort Trouble Shooting, HVAC Operation Outsourcing, Commissioning, Accurate Equipment Tune-ups, and Energy Services.

Keywords: data acquisition, energy performance, building diagnostics, HVAC systems, lighting systems

Expertise Required: Knowledge of typical HVAC, lighting or control systems operation is important to understand analysis results. A 2-day training course is available, as well as extensive on-line help, Internet home page technical support, phone support, and tutorial usage manual.

Users: 120 customers of MicroDataLogger data acquisition system, 25 users of ENFORMA software, 95% of customers are in U.S.

Audience: Tool is directed at energy service providers, HVAC service contractors, utilities, and the facility staff of large institutions.

Input: Operating schedule of the building in question, brief description of HVAC systems in building, system performance data from data loggers and building controls system as dictated by software.

Output: Plots of how HVAC, controls, and lighting systems are performing, sample plots that show how systems should be running, time series plots, user defined plots, energy load profiles, and reporting functions to document results of analysis. Software uses various filtering tools to control how data is shown, and automatically calculates deltas, offsets, standard engineering conversions of data streams. The user never has to deal with raw data in complicated spreadsheet sessions.

Computer Platform: 486 or above, running Windows 3.1, or 95.

Programming Language: C++

Strengths: Total integration of the building diagnostic process. Major time and cost savings from having the software define the metering plan, program the loggers, manage the resulting data, and guiding the user towards problem solutions using a built-in engineering knowledge base. Uses actual building system performance data to determine: baseline energy usage, system operation problems, potential maintenance issues, the need for retrofits or equipment replacement, reason for comfort problems, and load shapes for power purchasing.

Weaknesses: Requires the user to take the time to gather actual HVAC, controls, and lighting system performance data using our MicroDataLogger data acquisition system. Does not currently perform automatic system diagnostics, but that capability is in our development plans.

HVACSIM+

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

Simulation model of a building HVAC (heating, ventilation, and air-conditioning) system plus HVAC controls, the building shell, the heating/cooling plant, and energy management and control system (EMCS) algorithms. The main program of HVACSIM+ (HVAC SIMulation PLUS other systems) employs a hierarchical, modular approach and advanced equation solving techniques to perform dynamic simulations of building/HVAC/control systems. The modular approach is based upon the methodology used in the TRNSYS program.

Keywords: HVAC equipment, systems, controls, EMCS, complex systems

Expertise Required: High level of computer literacy.

Users: More than 100.

Audience: Building technology researchers, graduate schools, consultants.

Input: Building system component model configuration, simulation setup work file, boundary data file, and simulation control data. Weather data and thermal property data of building shell materials are also required, when building shells are included in a simulation.

Output: User-designed reports.

Computer Platform: PC-compatible, with 640 kilobytes of RAM and math coprocessor.

Programming Language: FORTRAN 77

Strengths: Dynamic response using variable time-steps; flexibility of model setup; interactive simulation model generation; simultaneous non-linear equation solving; stiff ordinary differential equation handling.

Weaknesses: High level of user computer literacy required; long calculation time when solving simultaneous equations.